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EVALUATION OF THE EFFECTS OF A PIPELINE FLOW IMPROVER ON AIRCRAFT FUEL SYSTEMS

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The US Air Force Reduced Scale Fuel System Simulator (FSS), the Extended Duration Thermal Stability Test (EDTST), and the Augmentor Vaporization Fouling Rig (AVFR) were used to evaluate the effect of pipeline drag reducing additives on aviation turbine fuels and aircraft fuel systems. The additive selected for this work was provided by Conoco Specialty Products and was designated CDR 102M. The additive was prepared in JP-8, JP-5 and Jet A and evaluated. In the first three runs on the FSS, a baseline JP-8 was used and additive concentrations were 50 parts per million by weight (wppm). The remaining test runs used either the JP-5 or the Jet A at 15 wppm additive. The bulk of this effort was completed using the Jet A fuel. Deposition quantification was determined through use of a Leco RC-412 Carbon Analyzer.

Data obtained during this program indicate that the presence of CDR 102M increases thermal stability deposition in areas where metal wetted-wall temperatures are 450°F or greater. In areas where wetted-wall temperatures were 425°F or lower, the presence of the additive had no conclusive effect on fuel deposition.

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FOREWARD

This report documents an over 2-year effort performed in-house at the Air Force Materiel Command, Wright Laboratory, Fuels and Lubrication Division, Fuels Branch under Project 3048, Task 304805, and Work Unit 30480537, "Advanced Fuel/Fuel System Evaluation". This effort was accomplished using the Reduced Scale Fuel System Simulator (FSS) and other supporting facilities at Wright-Patterson Air Force Base, Ohio.

The authors wish to acknowledge the following persons, without whose assistance, this effort would not have been possible: Messrs. James Shardo, Scott Bauser, Tim Gootee, Barry McMillan and Ms Margo Swensen. The authors would also like to acknowledge the literature research done by Lt Col Terry F. Roylance and his contribution to the preparation of the background information on Pipeline Drag Reducers, development of some of the illustrations, and in the technical editing of this report. The authors would also like to acknowledge the efforts of Captain Dennis Tuthill (USAF) and Mr Gordon Dieterle of the University of Dayton Research Institute for their work on the Extended Duration Thermal Stability Test and Dr Tim Edwards for his work on the Augmentor Vaporization Fouling Rig portions of this effort.

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LIST OF ABBREVIATIONS

ASTM . . . American Society for Testing and Materials
AVHX . . . Aiframe Heat Exchanger
BFA . . . . . Burner Feed Arm
CDR . . . . Conoco Drag Reducer
CDR102M Conoco Drag Reducer 102M
cm . . . . . . centimeter
cm^2 . . . . . square centimeter
cS . . . . centistokes (viscosity)
EDM . . . . Electrical Discharge Machining
EDTST . . Extended Duration Thermal Stability Test
FCOC . . . Fuel-Cooled-Oil-Cooler
FSS . . . . . Reduced Scale Fuel System Simulator
GPH . . . . . gallons per hour (US)
hr . . . . hour
I.D. . . . . . inside diameter
kW . . . . . . killowatt
mg . . . . . . milligrams
ml . . . . . . millililter
Mw . . . . . Molecular weight
N_{RE} . . . . . Reynolds Number
O.D.. . . . . outside diameter
P&W . . . . Pratt and Whitney (Specifically Pratt and Whitney Aircraft, West Palm Beach Florida.
PDRA . . . Pipeline Drag Reducer Additive
PPE . . . . . Polyphenylether
PSIA . . . . pounds per square inch, absolute
PSIG . . . . pounds per square inch, guage
T_{ww} . . . . . Temperature, Wetted-Wall
TAPS . . . . Trans-Alaskan Pipeline System
TE . . . . . . Temperature Element (thermocouple) - used to denote a specific thermocouple on the test article or facility
wppm. . . . parts per million, by weight
μg . . . . . . micrograms

SECTION 1
EXECUTIVE SUMMARY

The US Air Force Reduced Scale Fuel System Simulator (FSS), the Extended Duration Thermal Stability Test (EDTST), and the Augmentor Vaporization Fouling Rig (AVFR) were used to evaluate the effect of pipeline drag reducing additives on aviation turbine fuels and aircraft fuel systems. The additive selected for this work was provided by Conoco Specialty Products and was designated CDR®102M. The additive was prepared in JP-8, JP-5 and Jet-A and evaluated. In the first three runs on the FSS, a baseline JP-8 was used and additive concentrations were 50 parts per million by weight (wppm). The remaining test runs used either the JP-5 or the Jet-A at 15 wppm additive. The bulk of this effort was completed using the Jet-A fuel. The method used to run the FSS for Runs 0 through 4 consumed too much fuel so Runs 5 through 18 were run slightly different. It was noted during these first runs that there was significantly more deposit in the Burner Feed Arm (BFA) of the FSS with the additive present (at 50 wppm) than without the additive. Carbon burn-off tests were not conducted on these initial Runs as the test technique was not yet available. Deposit amounts were determined qualitatively by cutting the BFA in half lengthwise and observing the amount of deposits. For Runs 5 through 18, the carbon burn-off technique was available and was used to provide a quantitative measure of deposited carbon.

After all the test runs were completed and data compiled, it was concluded that the presence of CDR®102M increases the amount of deposition in areas where metal wetted-wall temperatures are 450 °F or greater. When wetted-wall temperatures exceeded 475 °F, the deposition results were more random, but in general tended to be greater for additive blends than for the straight baseline fuel. In areas where wetted-wall temperatures were in the 425 °F range, the presence of the additive had no conclusive effect on fuel deposition. Similar results were observed using the EDTST and the AVFR.

In conclusion, it is recommended that Pipeline Drag Reducing Additives (PDRAs) NOT be approved for general use in either military or commercial aviation turbine fuels. However, in the case of a crisis situation, use of PDRAs might be acceptable, realizing that there would be a resultant increase in fuel system related maintenance due to a faster rate of fuel deposit buildup with PDRA-

doped fuels. Depending on the situation, this might well be an acceptable trade-off to the improved fuel supply logistics that are possible with the use of a PDRA. It should be noted that this report does not address the issues of the effect of PDRA on ground fuel handling equipment such as pumps, fuel treatment equipment and filter separators.

SECTION 2
INTRODUCTION

HISTORY

In the early 1960's Conoco scientists began researching the application of drag reducing additives to the petroleum industry. They developed an effective drag reducer for hydrocarbon systems and patents followed in 1972. In 1977, critical needs arose to increase flows in the Trans-Alaska Pipeline System (TAPS). Conoco formulated what is now known as CDR® which was tested in the Alaskan system in 1979 with great success. It is still being used today. With this success behind them, Conoco researchers produced a substantially more effective product. This product was known as CDR®102M Flow Improver.

When the TAPS began using a CDR® in 1979, the flow rate was 1.3 million barrels a day. As time went on the flow rate has increased to 1.65 million plus, yet the mechanical capacity of the system is only 1.4 million barrels. In 1982, a test demonstrated that a throughput of 1.85 million barrels a day was achievable. Today, CDR® is being used in major pipeline systems all over the world. However, even though CDR® 102M is being used in a range of fluids from crude oils to gasolines, it is still not approved for use in jet fuels.

FLUID FLOW PRINCIPLES OF LAMINAR AND TURBULENT FLOW

Fluids can move through a pipeline by either laminar or turbulent flow. *Laminar Flow* occurs in the low flow velocity range (Reynolds Number (N_{RE}) below 2100) and is sometimes called streamline or viscous flow. In pipes, it is characterized by the gliding of concentric cylindrical layers of fluid past one another in an orderly fashion as illustrated in Figure 1. Flow is steady and smooth. Velocity of the fluid is greatest at the center of the pipe and decreases to zero at the pipe wall. Drag reducers do not work in the laminar flow regime.

Pipeline operators generally avoid the laminar flow regime because flow velocities and pipeline throughput are normally too low to be economically attractive. It is also impossible to "batch" different products down the line without mechanically separating them with a plug.

Turbulent Flow, sometimes called "plug" flow, occurs in the higher flow velocity range (Reynolds Numbers (N_{RE}) above 4000) - see Figure 1. Turbulent flow is characterized by irregular, random

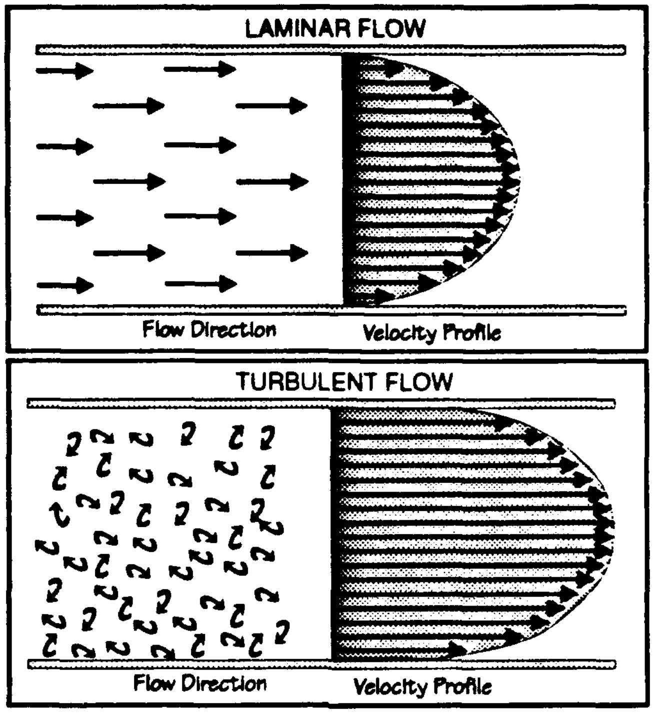

Figure 1. Laminar and Turbulent Flow Velocity Profile

motion of fluid particles in directions transverse to the direction of the main flow. The flow is unstable. Turbulent eddies are generated at the pipe wall and move into the core of the pipe. More energy is required to transport fluid at a given average flow velocity in turbulent flow because not all of the energy goes toward overcoming viscous resistance to motion down the pipe. Part of the energy is dissipated in the formation of eddy currents.

In most cases, a general family of polymeric chemical additives called "drag reducers" can decrease this turbulent energy loss. Generally, the more turbulent the flow, the more effective the drag reducer becomes and consequently, more efficient energy utilization can be achieved.

DRAG AND DRAG REDUCERS

"Drag" is a term that refers to the frictional pressure loss per length of pipe which develops when a fluid flows in a pipeline. Drag increases with increasing flow velocity. Drag reduction is the proportional decrease in this frictional pressure drop achieved with the addition of very small amounts of a specialty chemical which acts as a drag reducing agent, also called a *drag reducing additive* or a *flow improver*.

A pipeline drag reducing additive (PDRA) is typically a high molecular weight hydrocarbon polymer suspended in a dihydrocarbon solvent. When mixed with a fluid such as crude oil or refined petroleum products in pipelines, it changes the flow characteristics and reduces the flow turbulence in the pipeline. Studies have shown that the strength of the turbulent eddy currents at the pipe wall are reduced by addition of a drag reducer. Some believe that the PDRA absorbs part of the turbulent energy and returns it to the flowing stream. By lowering the energy loss or "drag", the PDRA allows the pipeline throughput to increase for a given working pressure, thereby increasing normal pipe capacity or throughput, or to operate at a lower pressure for the same throughput, thereby decreasing operating costs (Figure 2).

It should be noted that a PDRA does not work by being absorbed into or coating pipelines, but rather it is dissolved into and becomes part of the fluid. The PDRA is highly susceptible to shear stresses in a pipeline system and thus looses its effectiveness readily. This happens mainly as the internal shear stresses of the pipeline flow and geometry break the PDRA long chain molecules into smaller pieces. Thus, the PDRA must be added continuously to the pipeline fluid to maintain the desired level of drag reduction.

CDR® 102M FLOW IMPROVER

Conoco has developed a drag reducer called CDR®(Conoco Drag Reducer)102M. It is a second generation flow improver used in pipelines to reduce turbulence and improve the flow characteristics of crude oil or hydrocarbon products. CDR®102M is a solution of high molecular weight hydrocarbon polymer in a hydrocarbon solvent. It is prepared in a batch process using a proprietary process and catalyst. It is a very effective flow improver at concentrations in the range of well under

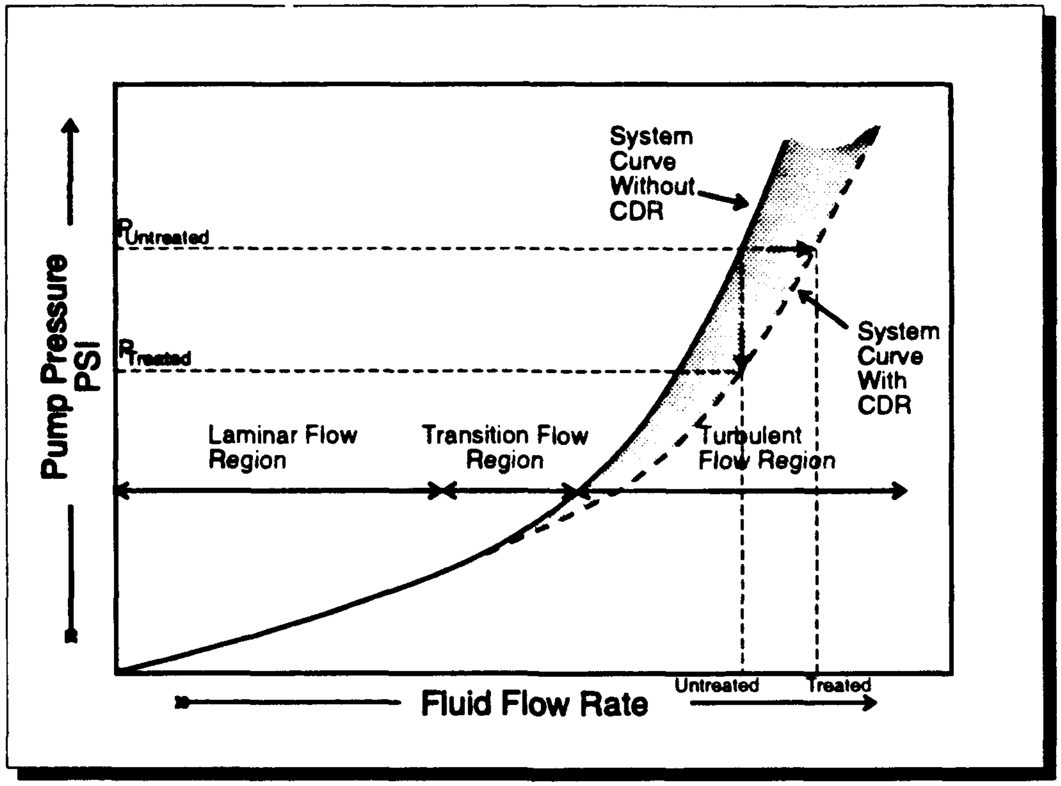

Figure 2. Pipeline System Performance

100 parts per million, by weight (wppm). Actual performance depends on the hydraulic characteristics of the pipeline and the physical properties of the liquid but up to a 40% increase in flow can be achieved with as little as 100 wppm CDR®102M. CDR®102M is typically injected directly into the flowing product on the output side of the pipeline booster pump.

DRAG REDUCER EFFECTS ON END USE EQUIPMENT

Of significant importance is the question of what effects drag reducers have on the equipment and operations that ultimately the end users must be responsible for. Previous work on drag reducers has mainly been accomplished by Conoco on its own Conoco Drag Reducer.[1,2] Both Conoco and the Trans-Alaska Pipeline System (TAPS) ran a set of bench tests prior to the use of CDR® in TAPS. In ASTM foaming tests, addition of CDR® had no significant effect upon the results. In desalting tests, no adverse results were seen on high-temperature emulsion stability. High-temperature heater tests were run and no heat exchanger fouling tendencies were observed. Coking of crude resids was evaluated with concentrations of CDR ® of up to 2,000 ppm (4 times the high of 500

ppm treating level for whole crude oil). The tests showed no observable effects. Two full-scale refinery test runs were also made. In a 36-hour test of 60,000 barrels of crude containing CDR®, no detectable effects in the operation of refinery units or in the process specifications of the products were observed. Specification tests were performed on gasoline samples containing 500 ppm of CDR®102M flow improver[3]. In the gum test, there was evidence of an increase in gums. Increases were also shown in the following areas of the standard gasoline specification test results:

» Gravity, API

» Octane number, motor

» Distillation, D86

» Existent gum, mg/100 ml

Diesel fuels were also evaluated and increases in the following specification tests for Diesel fuels with the flow improver of 500 ppm were noted:

» Gravity, API

» Viscosity, cSt @100 °F

» Carbon Residue

» Total gum residue

NATO ALPHA JET TEST 700 PPM CONOCO DRAG REDUCER

As a part of the development program for engine LARZAK 04 C20 an extended-time 200-cycle test was conducted at KHD Luftfahrttechnik as specified in Test Program Document No. 1.1138. At the request of Wehrwissenschaftliches Institute Fur Materialuntersuchung (WIM), Erding, a fuel (JP-8, Nato-Code F-34) was used to which a Pipeline Drag Reducer (PDR) had been added. The objective of the test was to determine the effects of PDR on the performance of aircraft fuel system components, including airframe and engine. Concerns were, and still are, that although the logistics of an improved flow capacity are extremely interesting, users of aviation fuel (for example, engine manufacturers, air forces) require assurances that the additive is harmless for aircraft operations.

The drag-reducing property of the PDR additive decreased to 0 from the mixing process in the fuel into the engine at KHD. The main cause for this seemed to be shearing in the pumps and during

transport. It is probable that the tank filling procedures, in particular the filter separator, will fully degrade PDR additive by the time it is added to the vehicle tanks.

The results of the evaluation of certain parameters such as the number of revolutions, thrust, exhaust temperature, specific fuel consumption and endoscopic test showed no significant influence of the PDR on the operation of the engine.

WRIGHT LABORATORY PIPELINE DRAG REDUCER TESTS

In late 1990, NATO Working Group 4 enlisted the assistance of the US Air Force in determining if use of pipeline drag reducing additives posed potential problems for military aircraft fuel systems. The Air Force, at the Fuels Branch, Aero Propulsion and Power Directorate at Wright-Patterson AFB, Ohio, possessed a rig which simulated an aircraft fuel system - - specifically the F-15 with the Pratt and Whitney (P&W) F100 engine. This facility was ideally suited for use in this endeavor. Work began in October 1990 to evaluate the effect of pipeline drag reducers on aircraft fuel systems, particularly from a thermal stability viewpoint. The results of this study are the subject of this report.

This research effort was the first such effort conducted using the Reduced Scale Fuel System Simulator (FSS). The initial runs (Runs 0 through 4) provided checkout of the system, refinement of test procedures and establishment of criteria for evaluating the test results. The results of Runs 5 through 18 provided the primary basis for assessing the CDR® 102M Flow Improver. All of the test run results will be discussed in Section 8, Discussion of Results.

SECTION 3
DESCRIPTION OF APPARATUS

Two major test rigs were used to complete this effort. One was the Reduced Scale Fuel System Simulator (FSS) and the other was the Extended Duration Thermal Stability Tester (EDTST). The Augmentor Fouling Rig (AFR) was also used. In the subsections that follow, each of these three systems will be described. Where fuel analyses were required, the appropriate laboratory or bench scale devices were used. Description of bench scale devices has been accomplished by others doing work in the area of thermal stability, and as such, the descriptions will not be repeated here.

REDUCED SCALE FUEL SYSTEM SIMULATOR (FSS)

Backgound

In 1987, the Boeing Military Airplane Company and Rolls-Royce Inc., Atlanta GA, jointly delivered a Reduced Scale Fuel System Simulator (FSS) to Wright-Patterson AFB. The FSS was designed to study the effects of current and advanced fuels on various aircraft fuel system components and, conversely, the effects fuel systems have on the chemical and physical character of jet fuels. It was fully automated with an extensive computer control and data acquisition system and was capable of unattended operation for extended periods of time (although this capability was not fully realized until just recently). The FSS was modified by Air Force engineers to assist in the development and certification of new aviation turbine fuels and the development of new fuel specifications and is currently being used for that purpose. It provides the most realistic and comprehensive simulation of aircraft fuel system thermal and flow environments in a small scale rig device available in the world.

The FSS consists of three major subsystems. These subsystems are the *Fuel Conditioning System*, the *Airframe Fuel System Simulator* and the *Engine Fuel System Simulator*. Figure 3 shows a block diagram of the FSS. The Airframe Simulator is designed around the F-15 at 1/40th scale and the Engine Simulator is designed around the Pratt & Whitney F100 at 1/100th scale. Scale factors for both systems were determined based on hardware component physical dimensions and Reynolds Number. The FSS control system has recently been revised to provide greater flexibility and to

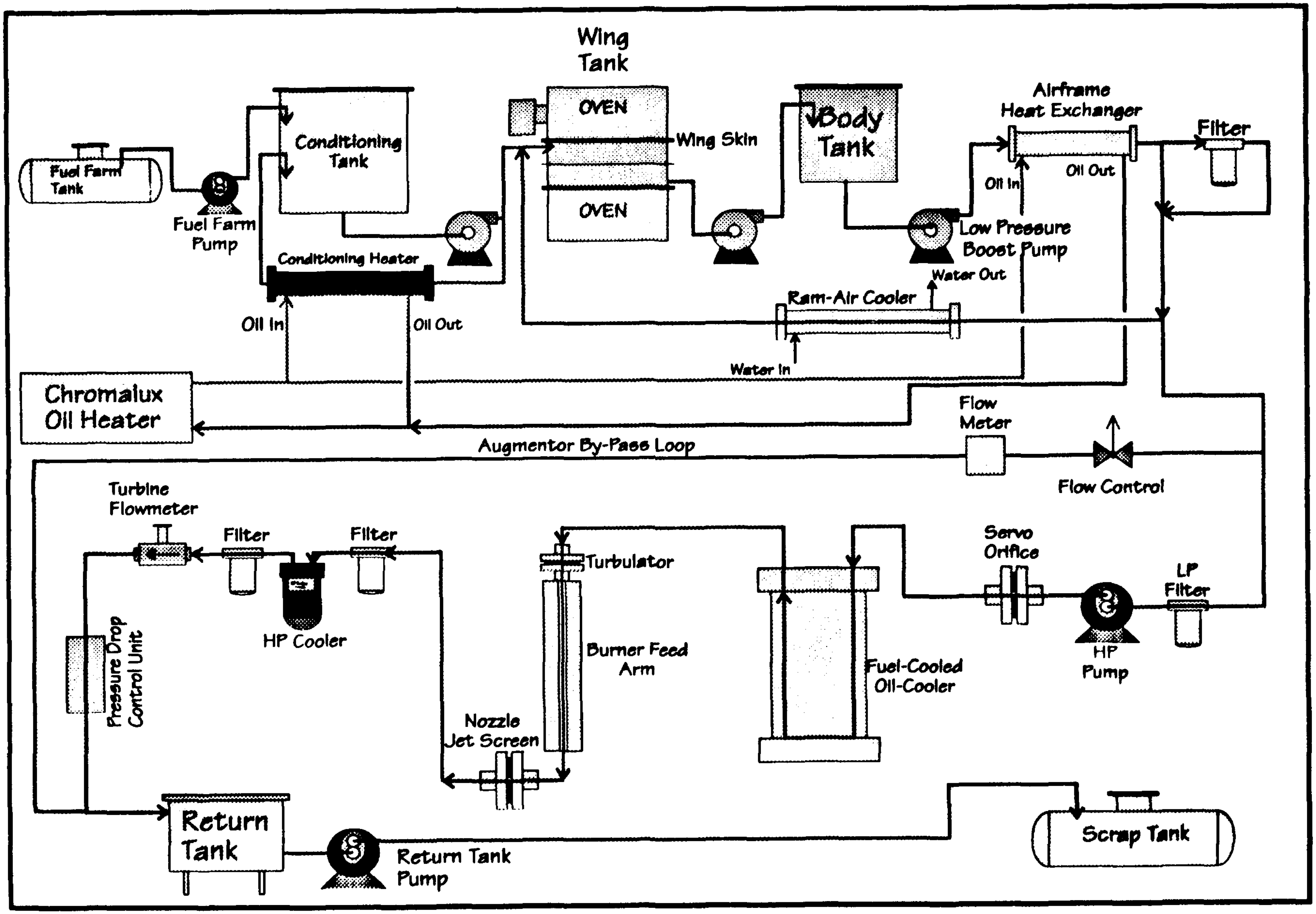

Figure 3 - Reduced Scale Fuel System Simulator (FSS)

increase overall system reliability. Very few changes have been made to the simulator (outside of the control system) since it was delivered and first made operational in 1987.

Fuel Conditioning System

In order to prepare fuel for use by the FSS, a tank was designed where fuel could be pre-conditioned. The *Fuel Conditioning System* is simply a single 60-gallon tank with a centrifugal pump, a shell-and-tube heat exchanger and a nitrogen injection valve. Conditioning can include pre-heating and deoxygenation by nitrogen sparge. This conditioning system is not currently capable of subambient conditioning. Figure 4 shows a diagram of this subsystem. Fuel preheating is accomplished by pumping fuel from the Conditioning Tank through a fuel/oil heat exchanger and back into the Conditioning Tank until the desired bulk fuel temperature (measured in the Condi-

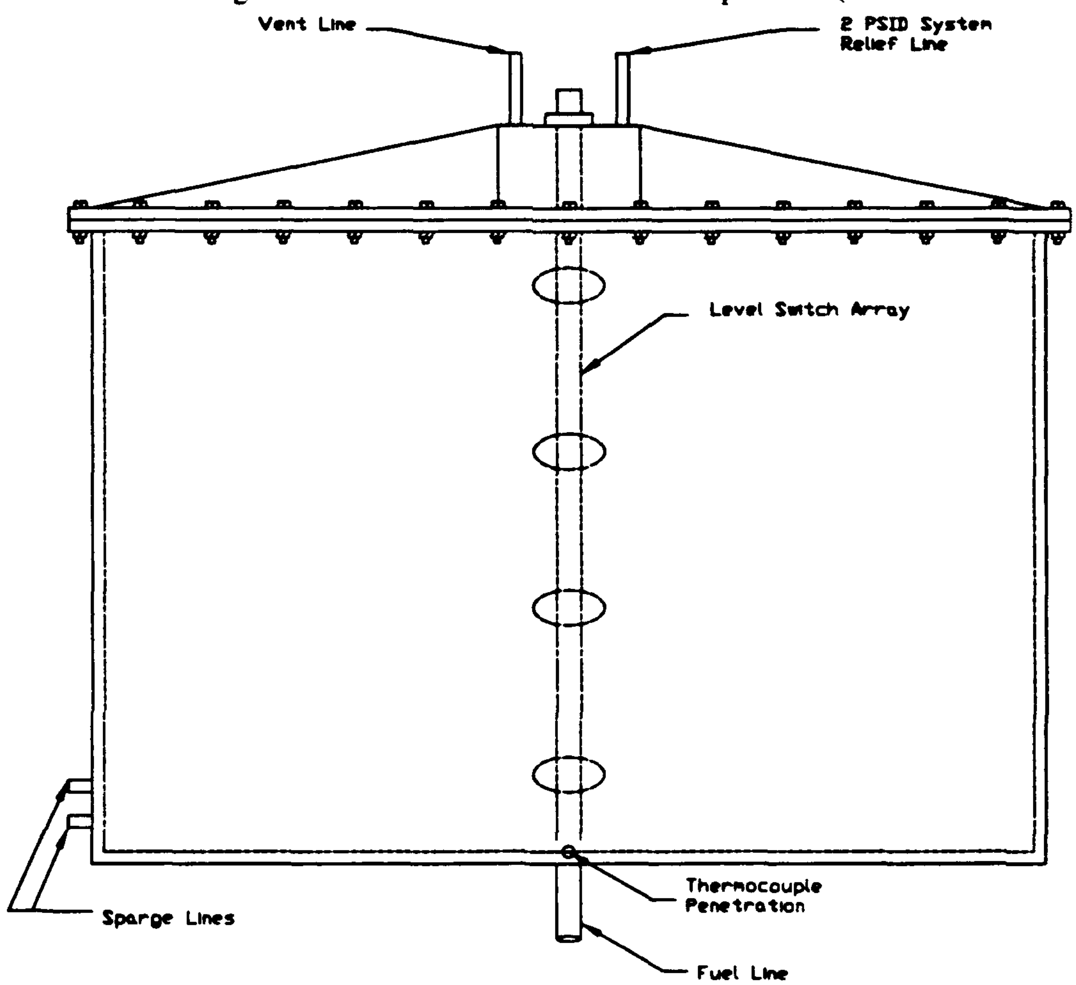

Figure 4 - Conditioning Tank

tioning Tank) is achieved. For this program, fuel was conditioned to 100 °F and no nitrogen sparge was used.

Airframe Fuel system Simulator

The *Airframe Fuel System Simulator* consists of four major components:

» Wing Tank
» Body (or Fuselage) Tank
» Low Pressure Boost Pump
» Airframe Heat Exchanger.

The Wing Tank (Figure 5) has a normal capacity of 20 gallons and is built in two small sections. One section can be removed leaving tank capacity at 10 gallons for simulation of thin wings. The Wing Tank is equipped with removable upper and lower skins for evaluation of material compatibilities. There are also two ovens, one above the upper skin and one below the lower skin which heat the upper and lower skins with radiant heat from internal quartz lamps. This allows simulation

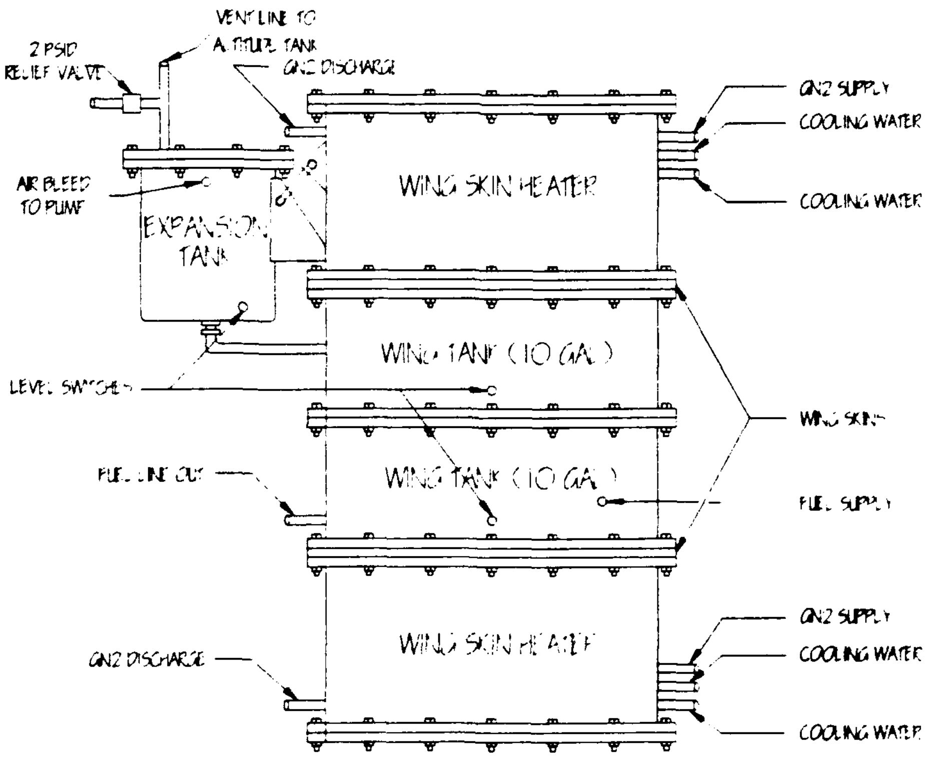

Figure 5 - Wing Tank

of aerodynamic wing skin heating. For the purposes of this effort, both upper and lower wing skin temperatures were maintained at 100 °F to minimize the normal cooldown of fuel while it awaits use in the Wing Tank. The Body Tank (Figure 6) has a capacity of 20 gallons and has no active heating or cooling mechanisms. It is simply a fuel reservoir. Fuel is transferred from the Wing to the Body tank periodically during the mission to keep the Body tank full at all times. This transfer is accomplished by a small centrifugal pump located between the Wing and Body tanks.

Fuel is transferred from the Body tank through the Airframe Heat Exchanger to the Engine Simulator. The boost pump is also a small centrifugal pump and operates continuously during the mission. Since this pump is capable of higher flow rates than the Engine Simulator requires, the boost pump is virtually dead-headed during the test. As a result of this dead-headed condition, fuel temperatures can reach 120 °F at the boost pump outlet with Body Tank bulk fuel temperatures in the vicinity of 95 °F.

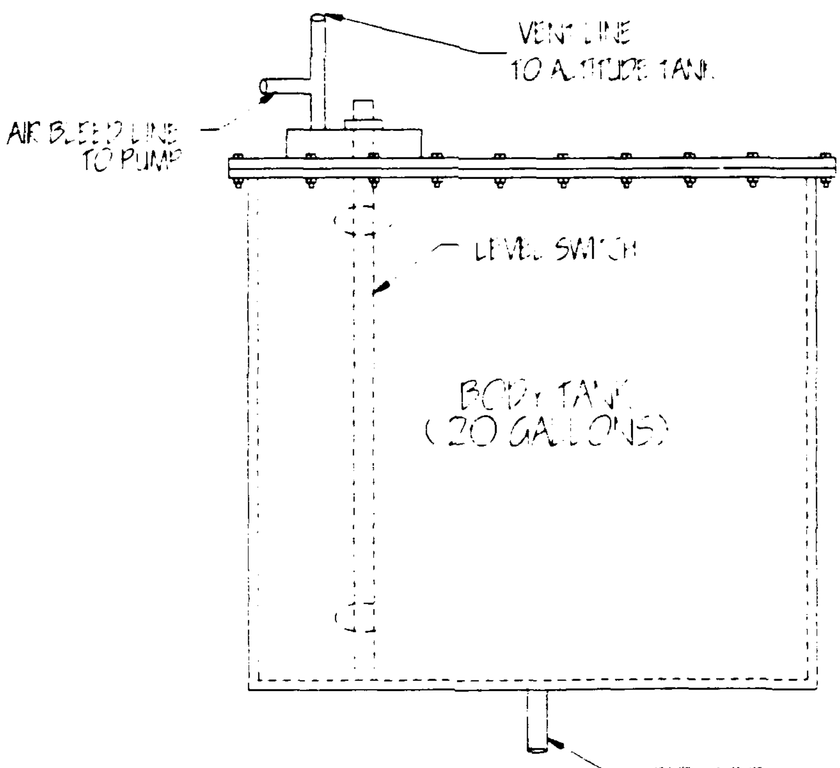

Figure 6 - Body Tank

The Airframe Heat Exchanger is used to collectively simulate all of the typical heat loads imposed on the fuel by the F-15 airframe system. This includes heat loads from avionics, environmental control, hydraulic and weapons systems. Fuel leaves this heat exchanger and passes to the Engine Simulator which is housed in the Engine Cabinet. The F-15 has a temperature design limit of 200 °F bulk fuel temperature at the Airframe/Engine interface. If fuel temperatures exceed this limit, then a recirculation valve is opened and fuel is sent back to the F-15 wing tanks and sprayed against the interior wing skin surface where it is cooled. In the same manner, the control on the Airframe Heat Exchanger is set to deliver 200 °F fuel to the Engine Simulator. If the bulk fuel temperature exceeds this limit, fuel is piped back to the Wing Tank through a water-cooled fuel heat exchanger. No attempt is made to control the amount of cooling that occurs in this heat exchanger. The Wing Tank does not have a provision for spraying fuel against the upper wing surface. In the Airframe Simulator, a filter has also been provided for use downstream of the Airframe Heat Exchanger to provide a point for qualitative and quantitative analyses of deposits and gums in the bulk fuel. This filter was not used in this program.

Engine Fuel System Simulator

The *Engine Fuel System Simulator* was the primary area of emphasis for this effort. Fuel deposition problems in the airframe fuel system of the F-15 are rare since the temperatures in these areas are not typically high enough to cause deposition. However, the airframe conditions play a critical role as a part of the fuel thermal history. This thermal history simulation is the main difference between the FSS and other small scale and bench top rigs.

The Engine Simulator consists of five major subcomponents:

» High Pressure (HP) Pump with its associated Low Pressure (LP) filter (Figure 7)

» Servo Orifice Simulator (Figure 8)

» Fuel-Cooled-Oil-Cooler (FCOC, Figure 9)

» Burner Feed Arm (BFA, Figure 10)

» Nozzle Jet Screen Simulator (Figure 13).

Each of these components simulates a specific section of the F100 engine.

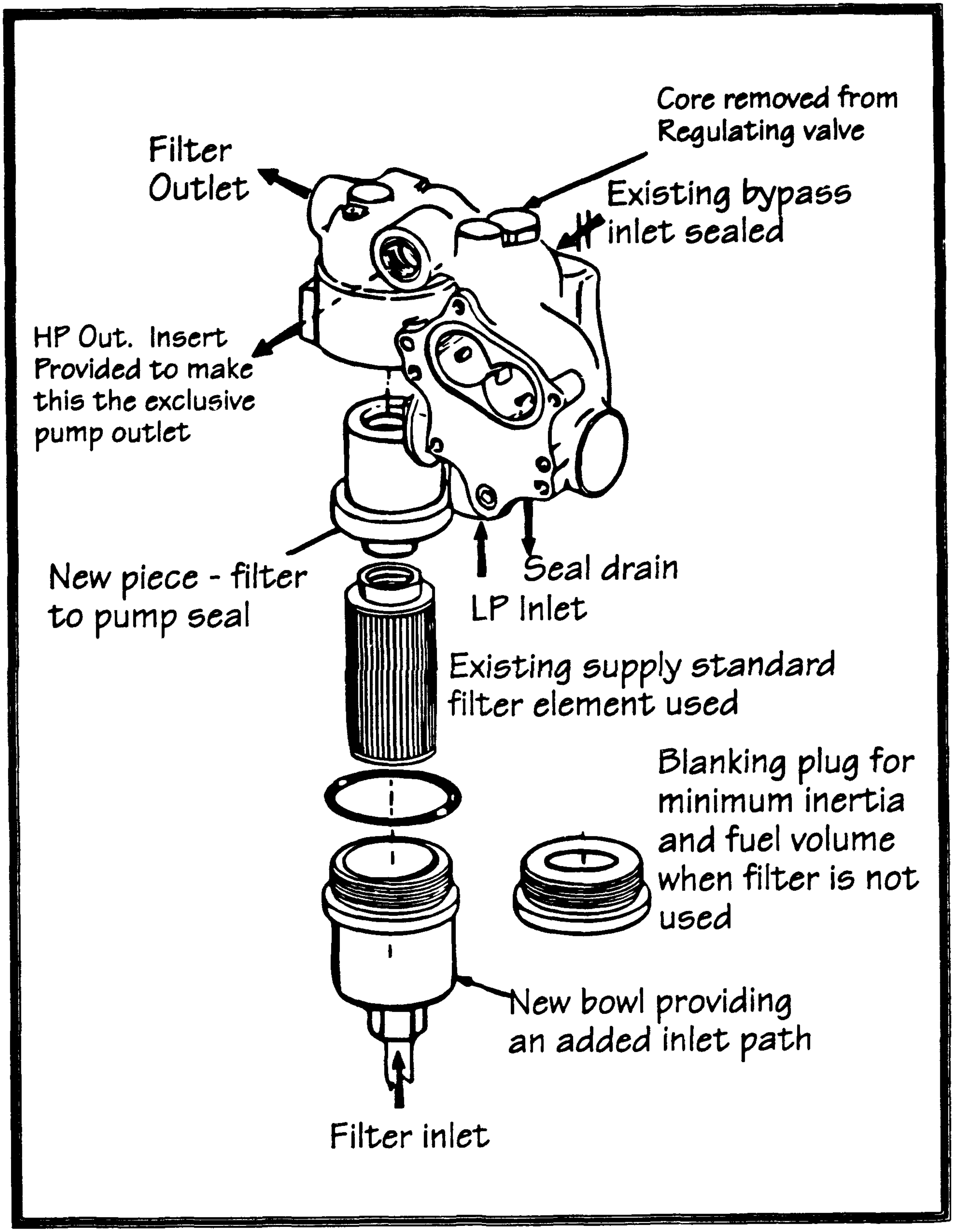

Figure 7 - High Pressure Engine Pump with Filter

The HP Pump with its integral LP Filter (Figure 7) is a Sundstrand pump (Part # 025323-010-03, typically used in the executive engine of the PT6 executive jet) that was modified for this specific application. It has internal fuel-wetted lead-bronze bearings which subjects the system to potential copper contamination. However, the use of copper alloy bearings is typical for most engine gear pump applications. The original Sundstrand pump incorporates a fine filter on the high pressure side of the pump. However, since the F100 contains only a low pressure filter, the Sundstrand pump has been modified to place the filter on the low pressure side (Figure 7).

Downstream of the HP Pump is the Servo Orifice Simulator (Figure 8). The purpose of this device is to simulate fuel passage through small orifices such as would be found in fuel controls. The device is neither actively heated or cooled. During a run, it is insulated to keep fuel temperatures

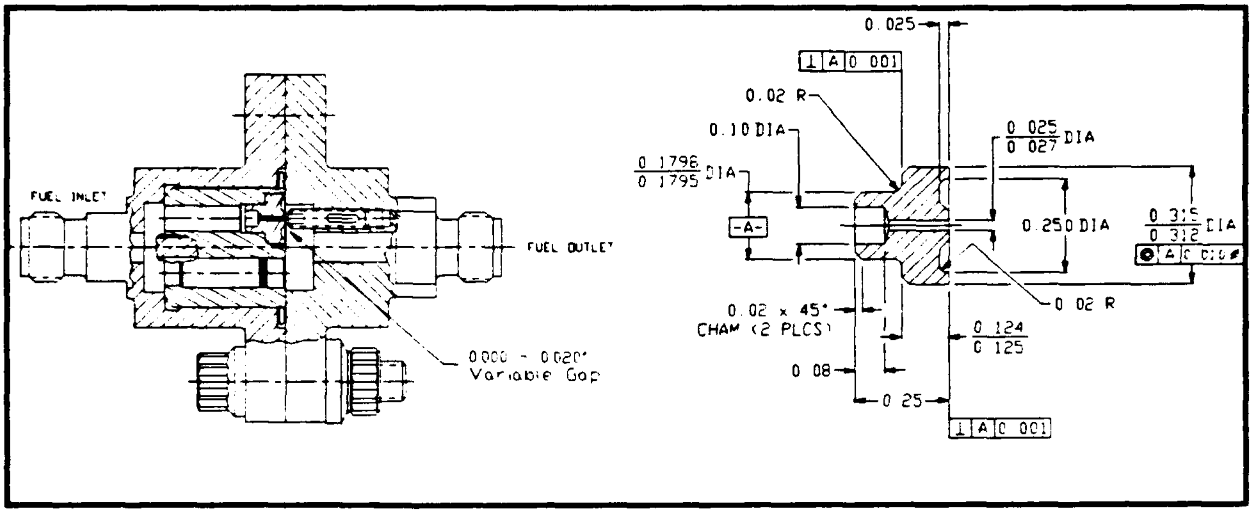

Figure 8 - Servo Orifice Simuator

from dropping too much since its metal-to-fuel mass ratio is extremely high. It has an internal check valve that opens when pressure drop across the orifice exceeds 60 psig (due to orifice blockage). Data obtained from this device include visual inspection for deposits, carbon burn-off analyses on the internal components and monitoring of pressure drop across the orifice.

The next component after the Servo Orifice Simulator is the Fuel-Cooled-Oil-Cooler (FCOC, Figure 9). This device simulates the cooling of engine oil by the fuel. The FCOC in the F100 engine consists of 576 tubes (288 forward flow and 288 return flow) that are 10.415 inches (26.454 cm) long and 0.125 inch (3.175 mm) O.D. The simulated FCOC contains six of these same tubes with

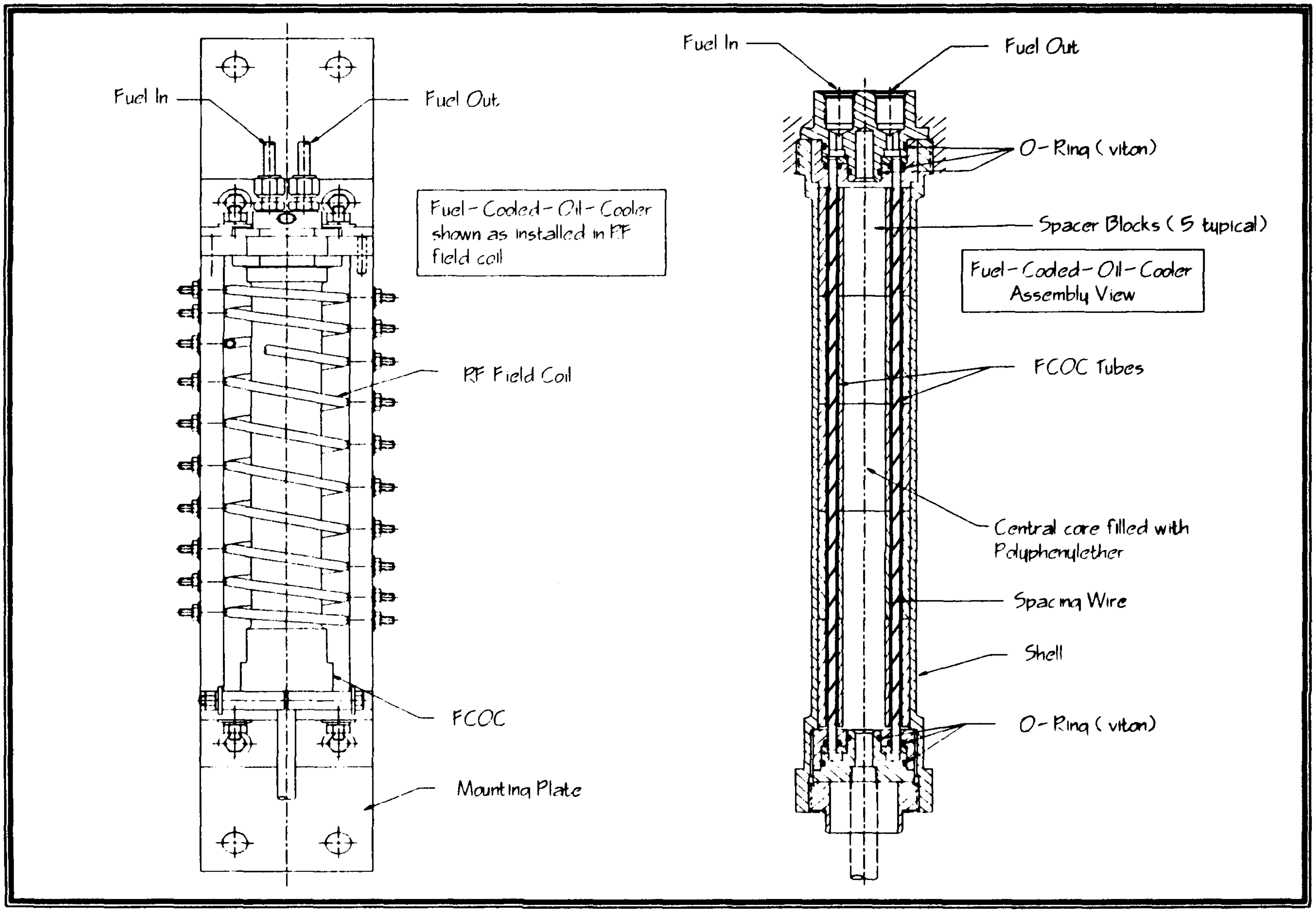

Figure 9 - Fuel-Cooled-Oil-Cooler (FCOC)

three for forward flow and three for return flow. These tubes are held in place by O-rings in a manifold arrangement and are placed inside aluminum spacer blocks so that they stay in alignment. The entire assembly (tubes and spacer blocks) is contained in a stainless steel shell. Polyphenylether (PPE) is then used to fill up the shell so that there is good thermal contact amongst all the internal components and the shell wall. This is then placed in the RF Induction field coil of a 2.5kW induction heater made by Lepel. Other means of heating were investigated during the design phase of the simulator, but RF Induction was chosen for its ability to accurately control the temperature while maintaining good transient response. Bulk fuel outlet temperature is controlled for this unit during a run and is typically held at 300 °F. The FCOC is instrumented with eight internal thermocouples - - one on each internal tube and two that float internally to measure PPE temperature to guard against overheating. In addition to these internal thermocouples, two thermocouples are typically attached to the outer shell to measure shell temperature. The FCOC was not considered a test article in the PDRA evaluation because of the difficulty in effectively removing PPE residue from the tubes prior to carbon burn-off. The FCOC is currently being redesigned to eliminate this problem.

Downstream of the FCOC is the Burner Feed Arm (BFA, Figures 10 and 10a). This device provides simulation of the fuel manifold pigtail that connects the nozzle assembly to the fuel manifold and is the major test article for the PDRA studies. It consists of a 12-inch (30.48 cm) section of straight tube with an O.D. of 0.5 inch (1.27 cm) and an I.D. of 0.075 inch (1.9 mm). In order to maintain the necessary degree of turbulence at the entrance to the BFA, a Turbulator Assembly (Figure 12) is included upstream of the BFA. This unit consists of a simple orifice and a screen. The BFA itself is instrumented with 10 thermocouples along its length. Each thermocouple is placed in a 0.023-inch (0.58 mm) diameter hole. The tip of the thermocouple is just 0.090 inch (2.28 mm) off the inner wall surface. These thermocouple readings are referred to as the wetted-wall temperatures in this report. Figure 11 shows the thermocouple placement for the BFA. In addition to these 10 thermocouples, another 4 are attached to the exterior skin of the BFA and are used to make sure temperature limits are not exceeded. The entire BFA assembly is placed in an RF induction field and heated using a Lepel 2.5 kW induction heater. Only 10 inches of the 12-inch- total length of the BFA is actively heated.

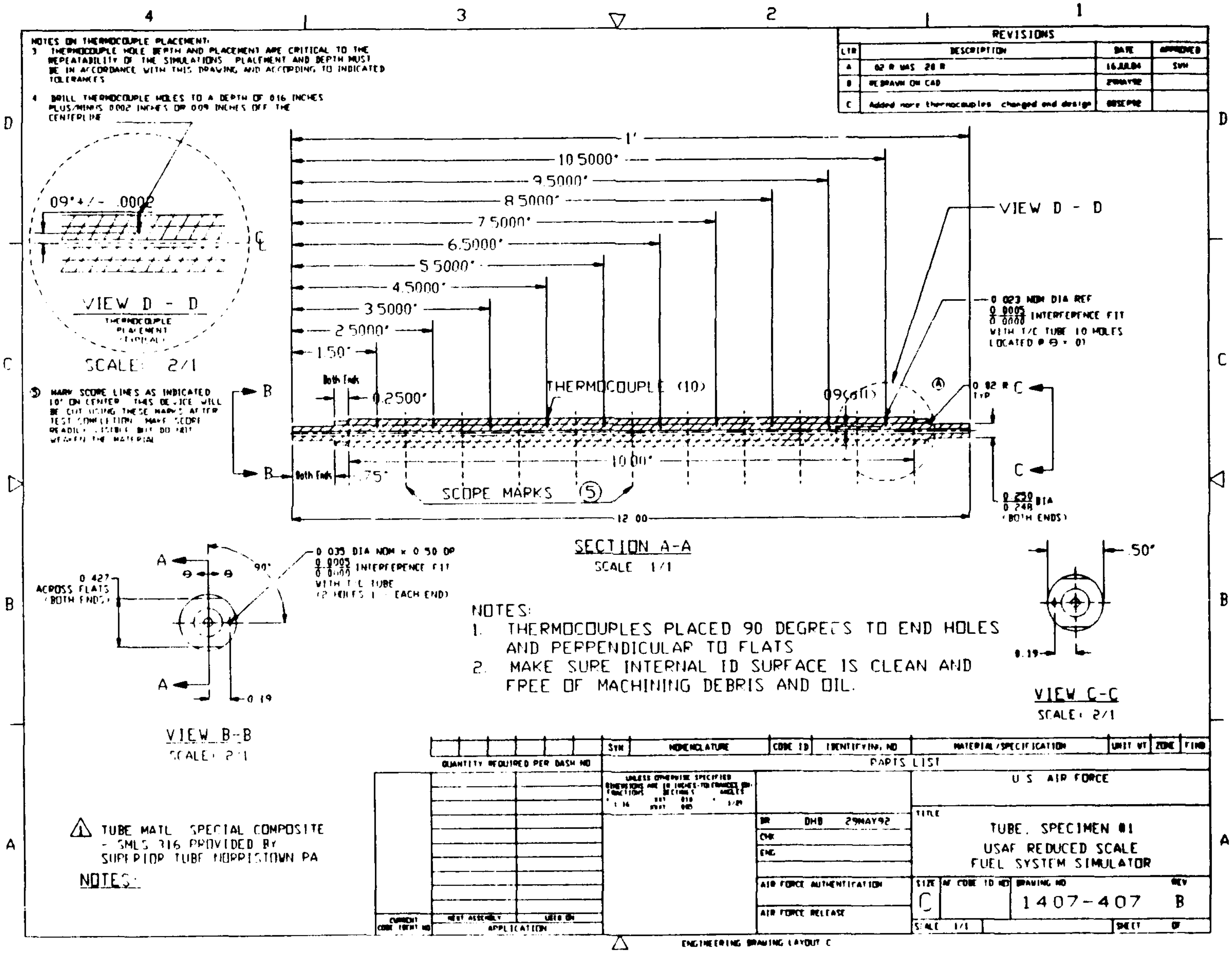

Figure 10 - Burner Feed Arm (BFA)

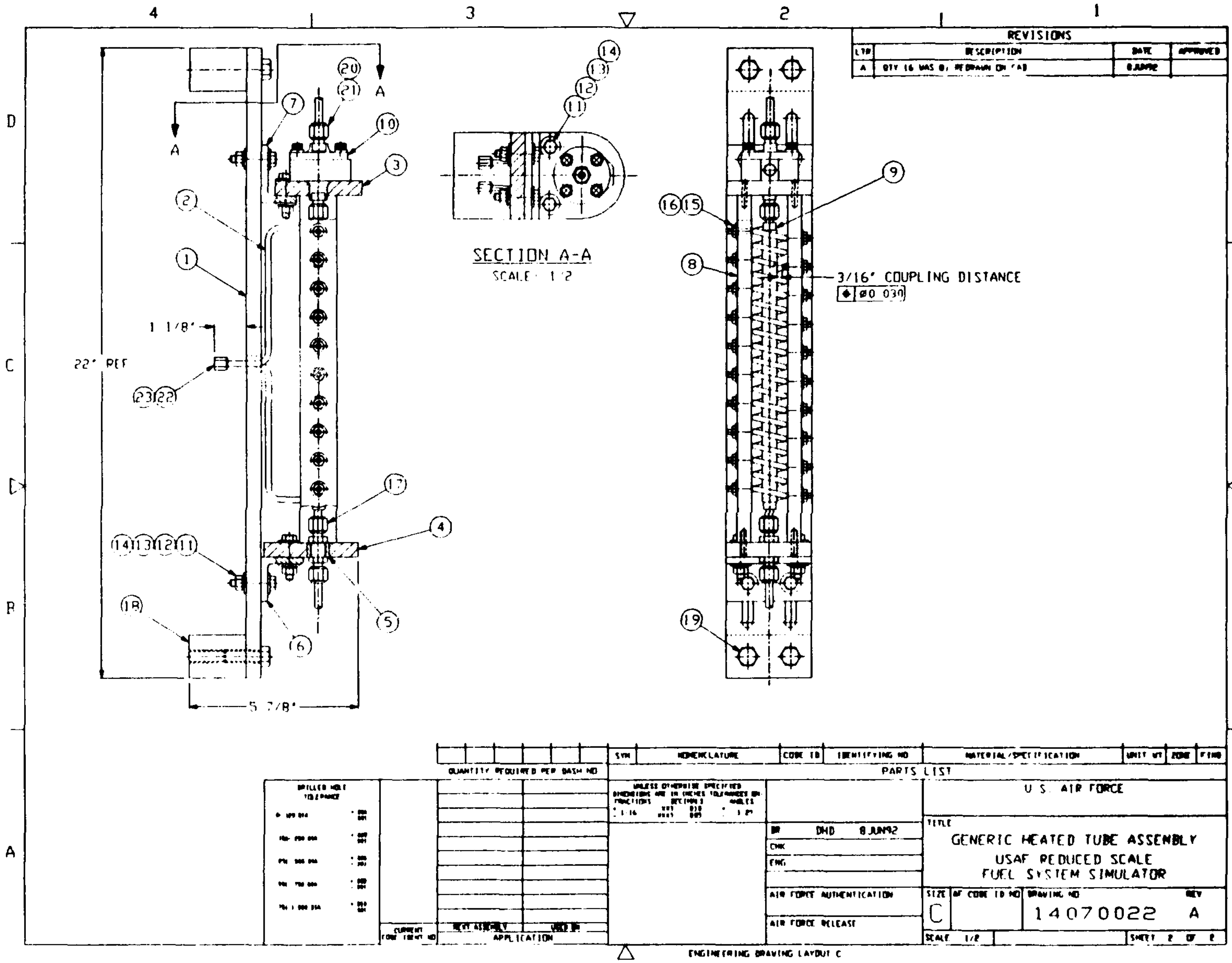

Figure 10a - Burner Feed Arm Installation

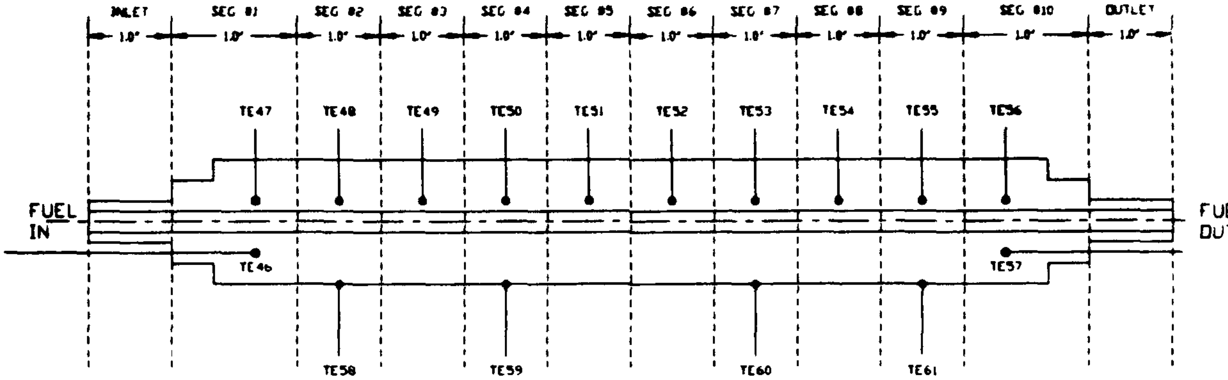

Figure 11 - BFA Thermocouple Placements and Identification

The final simulation element is the Nozzle Jet Screen Simulator and is downstream of the BFA . It is set in the hot fuel discharge from the BFA. It's purpose is to catch flakes of deposits from upstream components such as the BFA. These deposit flakes can lead to nozzle blockage in the actual aircraft system. It consists of a simple screen with drilled holes that are 0.020 inch (.5 mm) in diameter. This screen can be replaced with other screens with smaller or larger holes - - depending

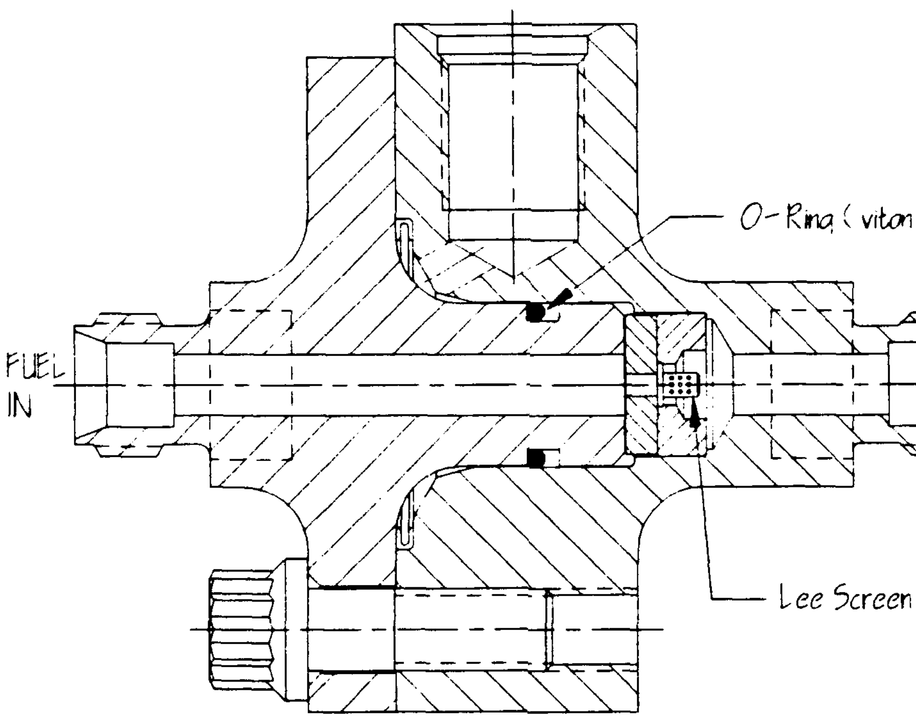

Figure 12 - Turbulator Assembly

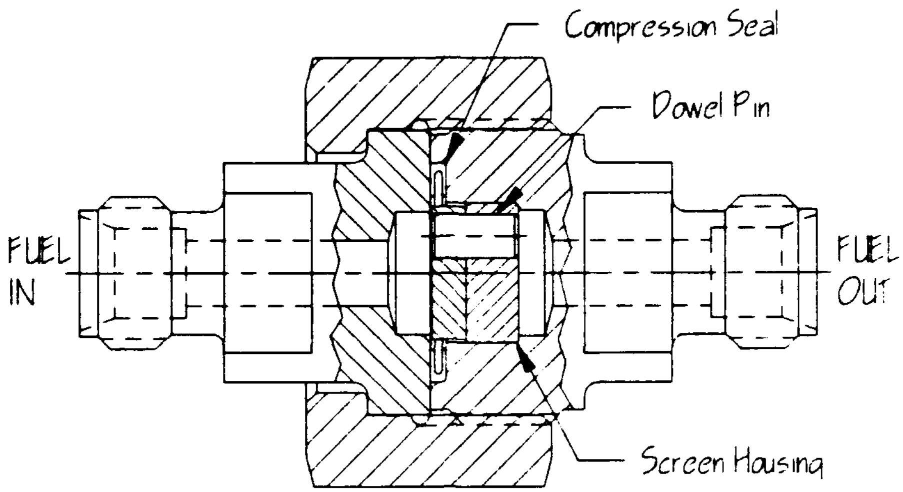

Figure 13 - Nozzle Jet Screen Simulator

upon the simulation application. Once the test is completed, the screen is removed and subjected to carbon burn-off analysis.

EXTENDED DURATION THERMAL STABILITY TEST (EDTST)

Background

Due to the length of time and amount of fuel required to complete a test on the FSS, a system was sought to provide a means of prescreening fuel additive blends by simulating critical fuel system parameters on a smaller scale. At the same time, such a test device could provide critical guidance to optimize the use of FSS test time and fuel. In addition, this would provide a system of "checks and balances" to assure that the FSS was relaying meaningful data.

The Extended Duration Thermal Stability Test (EDTST) was developed and used to obtain supporting data for this program. The EDTST was developed from an existing in-house rig previously called the *Hydrogenation Reaction System (HRS).* This rig was used in the early 1980's to evaluate process conditions and catalysts in the development of endothermic and high density fuels. It is computer controlled and capable of long-term unattended operation. Its basic structure and capabilities made it applicable to this effort. The EDTST consumes far less fuel than the FSS and lends itself readily to use as a pre-screening device.

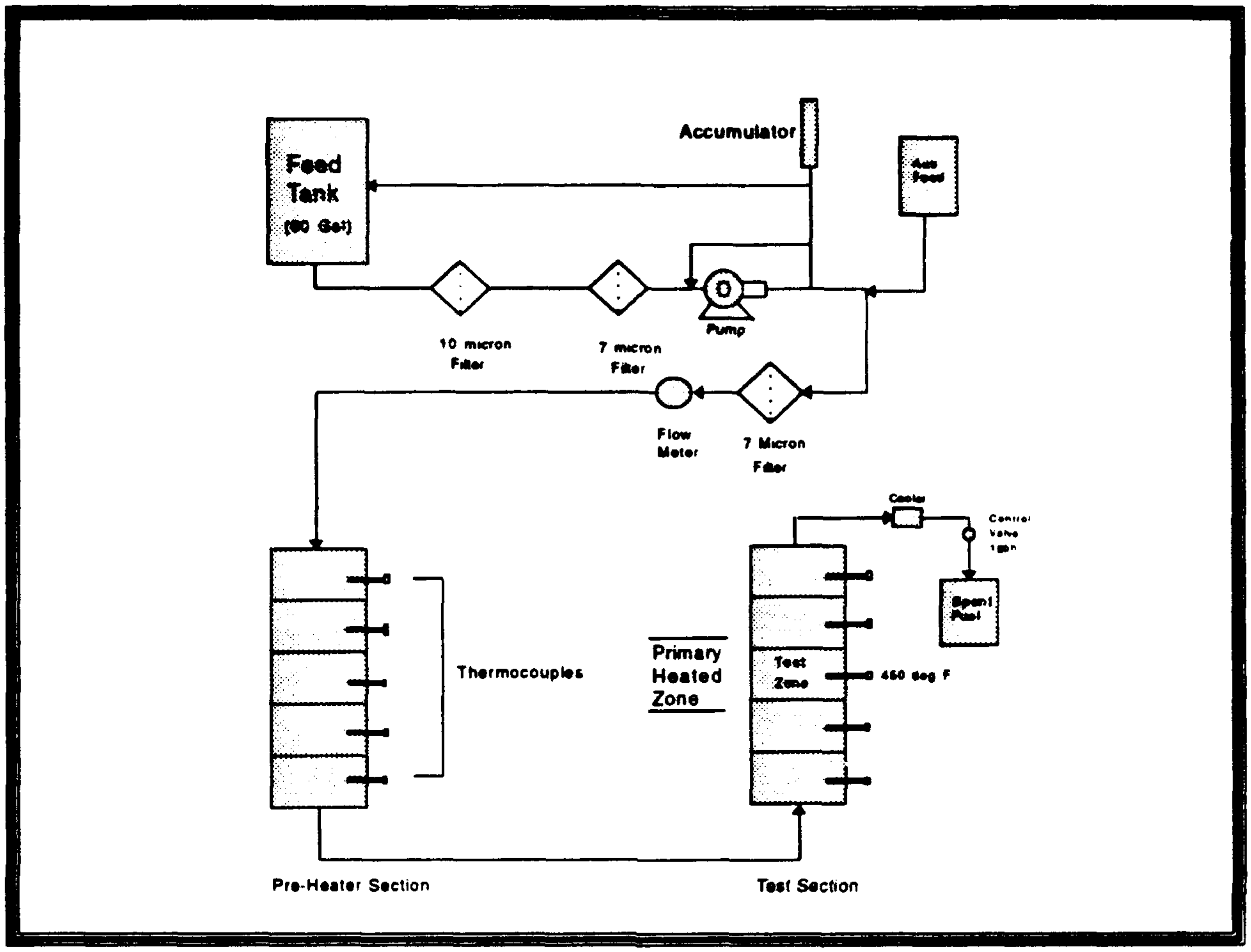

Figure 14 - EDTST Block Diagram

Modification of the HRS to construct the EDTST consisted of replacing existing pumps and fuel tanks and the addition of selected filters, control valves and a flow meter. A schematic of the system is shown in Figure 14. The fuel pump is capable of 1 GPM at 500 psig. The fuel tank is constructed of 316 stainless steel and has a capacity of 60 gallons which allows the EDTST to be operated for up to 50 hours (at typical conditions) without having to be refilled.

Preheater SubUnit

There are two main subunits on the EDTST. The first subsection is the *Preheater Section*. The Preheater Section includes a preheater assembly that is constructed of a 64-inch (1.62 m) long, 0.25-inch (6.35 mm) O.D. 316 stainless steel preheater tube with a nominal wall thickness of 0.035-inch (0.889 mm). This preheater tube is contained inside a thick walled furnace tube that is 1-inch(25.4 mm) I.D. and 2-inch (50.8 mm) O.D. The annular space between the furnace tube I.D.

and the preheater tube O.D. is filled with sand. This preheater assembly is shown in Figure 15. The preheater assembly is heated by a clam-shell furnace with five independently controlled zones and is capable of operating to 1800 °F (982 °C). These five zones form a total heated length of 32 inches (81.3 cm). The temperature in each zone is measured by two thermocouples located at the center of each furnace zone - - one on either side of the furnace tube. One thermocouple in each zone is used to control the heat input from the clam-shell furnace. The other thermocouple for that zone is used as an input to the EDTST safety controls. All five zones of the preheater furnace are used to maintain a constant bulk fuel temperature out of the preheater section. The preheater tube itself has a thermocouple located at its midpoint to monitor its outer wall temperature.

Test Section SubUnit

The second subunit, the *Test Section*, is shown in Figure 16. The Test Section consists of an arrangement of a furnace, furnace tube and a test tube similar to the *Preheater Section*. The test tube is a 56-inch (1.42 m) long, 1/8-inch (3.175 mm) O.D. 316 stainless steel tube with a 0.035-inch (0.889 mm) wall. The test tube is heated by only the middle zone (test zone) of the five-zone in the clam-shell furnace. The two zones on either side of this middle zone are controlled at a low temperature to maintain the desired bulk fuel temperature into and out of the test zone. The test tube has five thermocouples mounted on its surface. Three of these thermocouples are located inside the test zone while the remaining two are located in the middle (approximately) of the adjacent zones. There are additional thermocouples located at the inlet and outlet of the preheater and test assemblies for measuring bulk fuel temperature at these locations.

Because the EDTST is instrumented for automatic control and alarm capabilities, it is typically operated unattended around-the-clock.

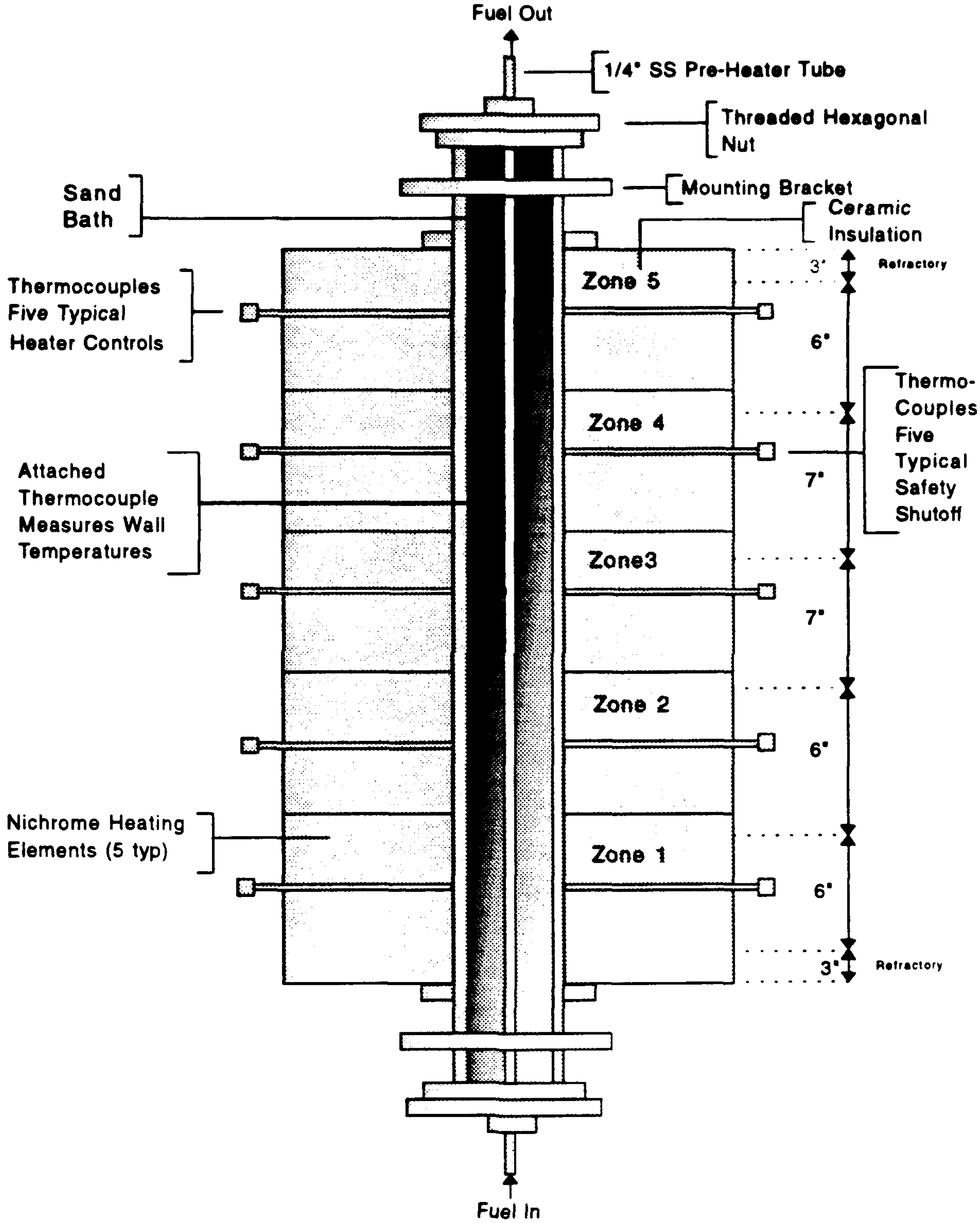

Figure 15 - EDTST PreHeater Assembly

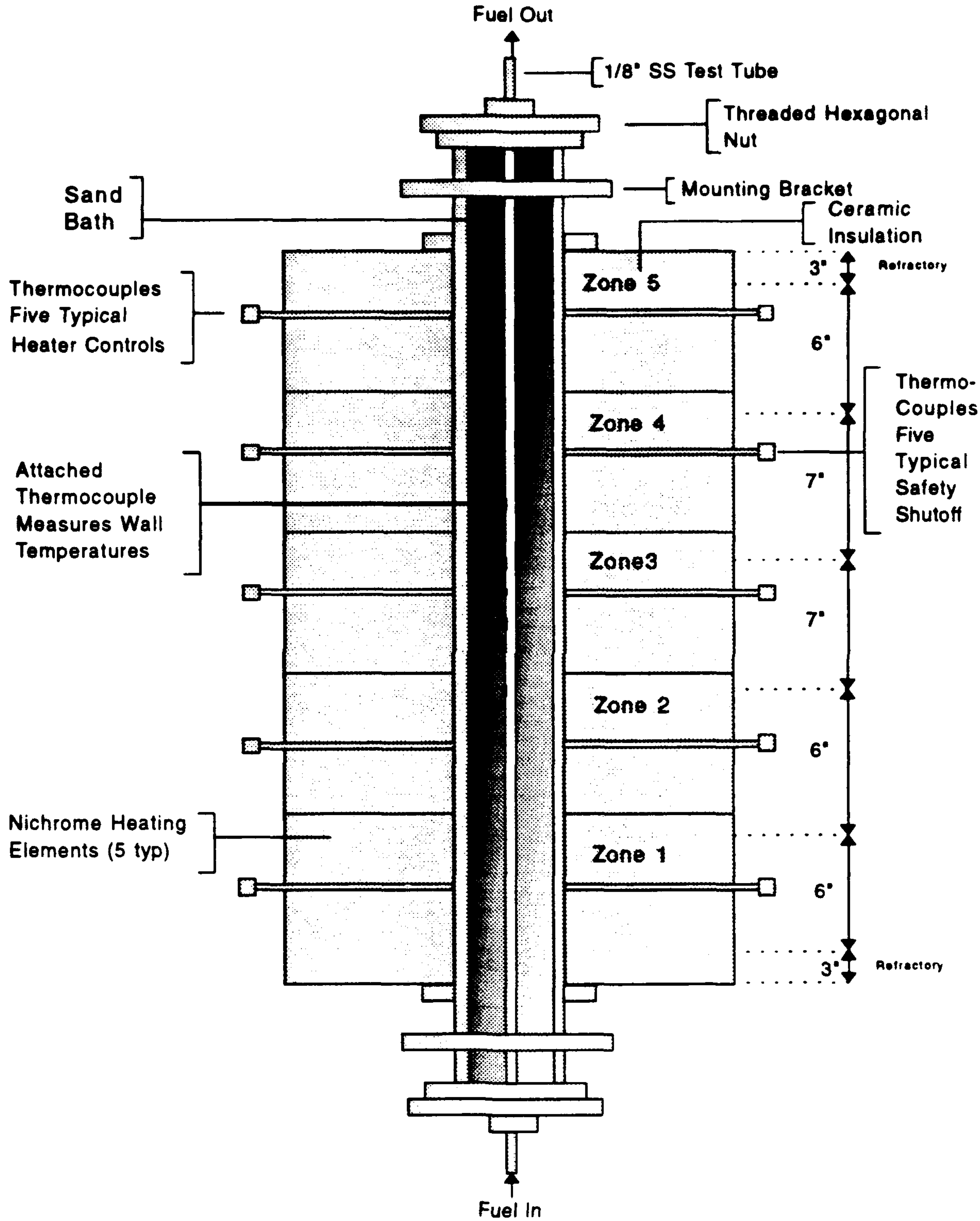

Figure 16 - EDTST Test Section Assembly

AUGMENTOR VAPORIZATION FOULING RIG (AVFR)

Background

The Augmentor Vaporization Fouling Rig (AVFR) is a small bench-scale apparatus which was constructed to study the the fuel deposition that occurs when a hydrocarbon fuel vaporizes[4]. This is of particular interest in augmentor (afterburner) systems. Deposition in augmentor spray rings and bars can adversely affect augmentor fuel spray patterns and can lead to combustion instabilities. These instabilities manifest themselves as "rumble" and can cause physical hardware damage if left unchecked. The deposition that causes these instabilities is thought to stem from either the vaporization of small amounts of fuel (in the order of milliliters/minute) that leak into hot augmentor sections or the vaporization of small amounts of the residual fuel present in these sections after the augmentor is shutdown. The AVFR was designed to study this vaporization, understand the mechanisms involved in the deposition process and then to find a way to stop it. It was selected for inclusion into this effort because it is able to simulate the augmentor environment - - something the FSS cannot do.

Apparatus Description

A schematic diagram of the AVFR is shown in Figure 17. Fuel is gravity-fed from an air- or nitrogen-sparged tank to a pump. The fuel pumped through approximately 3 feet of 1/16-inch O.D. tubing into a three-way valve. This valve serves to select whether fuel or nitrogen is flowing through

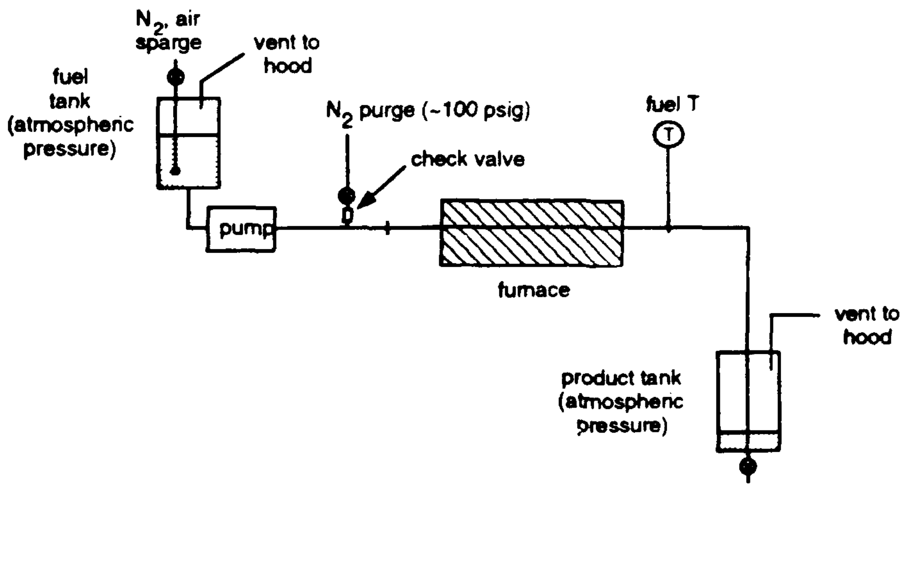

Figure 17. Augmentor Vaporization Fouling Rig

the heated section of the apparatus. After the three-way valve, the fuel flows through a 1/4-inch O.D. tube. Type K (chromel/alumel) thermocouples are spot welded along the length of this tube and the entire assembly is inserted into a 1-inch tube. Sand is packed in the annulus formed by the tubes to minimize convective air currents around the inner tube. This assembly is then placed inside a "clam-shell" furnace (Lindbergh Model 55035). After leaving the furnace, fuel flows through a condensor tube and then into a vented collection tank.

SECTION 4
EXPERIMENTAL PARAMETERS

Overall Technical Approach

The approach for this effort was to operate the FSS at typical F-15 operating conditions using both the baseline fuel and fuel with PDRA. Following each run, key components would be disassembled and inspected. Any deposition would be quantified by carbon burn-off techniques. Any changes in deposition quantity, quality or morphology would be noted and reported.

Initially, an additive concentration of 50 wppm was selected because this was thought to be the maximum amount of PDRA likely to be present in the fuel at any one time, even under extreme circustances. This was later reevaluated and the significant portions of this test program were performed with 15 wppm.

To support the FSS runs, other tests, both rig scale and bench scale, were utilized to provide collaborating information. The primary test device which provided colloborating data was the Extended Duration Thermal Stability Test (EDTST). This system is discussed in Section 3.

REDUCED SCALE FUEL SYSTEM SIMULATOR(FSS)

Operation Parameters

One of the main benefits of the FSS is its ability to operate in various modes. Operation modes can be as complex as "flying" mission cycles (simulating every phase of aircraft operation from engine start, through takeoff, landing and engine shutdown) to as simple as steady-state operation at a

Table 1. Modified High Altitude Intercept Mission

Mission Phase	Time In Phase
Engine Start	1 min.
Taxi/Takeoff/Climb	11 min.
Cruise Out	42 min.
Cruise Back	42 min.
Idle Descent	20 min.
Land/Taxi/Shutdown	4 min.

selected set of conditions. For the purposes of this program, the FSS was initially operated using complete missions. This was later changed to minimize run time and fuel consumption. A 120 minute, high altitude intercept mission was selected.[5] This mission profile was modified by eliminating the intercept segment of the mission because it didn't impact the thermal aspects of the system, would simplify simulator operations, and minimize fuel consumption. Table 1 presents the phase and duty cycle of this modified High Altitude Intercept Mission.

Once the mission sequencing was determined, a review of engine and airframe hardware components was conducted to determine the temperatures, pressures and flow rates associated with particular areas of interest. The review focused on high temperature engine components that are currently seeing fuel deposition phenomena or where there was significant concern that a high molecular weight polymer might instigate deposition. Fuel flows were calculated using the F-15 Flight Manual[6], and, based on FSS scaling factors, and the mission flight profile established for the run. Component temperatures were determined from thermal models of the F100 engine conducted by Pratt & Whitney, Government Products Division and F-16/F100 qualification tests[7]. Table 2 shows the inlet and outlet temperatures determined from this data. It is important to note that BFA wetted-wall temperatures were determined based on a thermal model of a fuel nozzle used in the F100 engine. This model showed wetted-wall hot spot temperatures ranging from 450 °F to 492 °F in a clean, unfouled nozzle. Bulk fuel temperatures into the nozzle were about 300 °F while fuel exiting the nozzle was about 325 °F.

Table 2 - FSS Mission Operating Temperatures

COMPONENT	BULK FUEL TEMPERATURE INLET	BULK FUEL TEMPERATURE OUTLET	WETTED-WALL TEMPERATURE
Airframe		200 °F	
High Pressure Pump	210 °F	250 °F **	
FCOC	250 °F **	300 °F	
BFA	300 °F	350 °F	450 °F Hot Spot

*** FCOC inlet temperatures in the F100 were predicted to be higher but these temperatures could not be duplicated in the FSS due to the scale of simulation. The FSS HP Pump metal mass-to-fuel mass ratio is significantly higher than in the F100 engine. This minimizes the temperature rise across the HP Pump for the FSS.*

Fuel component manufacturers were also consulted and those discussions confirmed that the proper operating temperatures had been selected for the FSS for this program. They also stated that future engine treends are toward higher bulk fuel temperatures and/or nozzle wetted-wall temperatures. The evaluations of wetted-wall temperatures of 475 °F to 485 °F were included in the program to address these potential higher temperatures. In addition, WL/POSF has undertaken a program to develop a new fuel (JP-8+100) to address this engine trend. The goal of that program is to develop a fuel whose thermal stability characteritics at are 100 °F higher than for current typical JP-8.

Mission Implementation

Fuel consumption for Runs 0 through 4 was about 3,000 gallons per single 85-hour run. This was considered extensive. It was obvious that completion of the PDRA evaluation with these fuel usage rates would take a significant amount of fuel. The operation of the FSS was, therefore, modified to minimize fuel consumption without impacting test and simulation integrity. The initial runs were examined to determine how much mission time was spent "at condition" (where test articles were at operating conditions typical of either high altitude cruise or idle descent). Components such as the FCOC and the BFA were "at condition" only about 90 minutes out of the 120-minute mission. The drain-down time between each mission added a significant cool-down period to each mission and wasted fuel by draining what was left in the tanks back to the fuel farm for disposal. At least 50% of the fuel initially brought on-board was by-passed through the augmentor flow control loop (see Figure 3) as scale correction flow without ever being used in the engine portion of the simulator. The FSS was designed with flow scale correction because the airframe portion of the FSS is scaled at $1/40^{th}$ of the F-15 airframe and the engine portion is scaled at $1/100^{th}$ of the Pratt & Whitney F100 engine. The thermal impact of repeated takeoff and climb segments, as well as landing, taxi and shutdown segments added little to the thermal stressing of the fuel due either to high fuel flows or lower operating temperatures for those segments. These low thermal stress segments could, therefore, be eliminated, resulting in significant savings in time and fuel usage without adversely affecting the viability of the test. Therefore, four missions were chained together into a *mission set* and the intermediate takeoff, climb, taxi and shutdown and tank drain segments were eliminated. Table 1 shows the sequencing of a standard single mission. Table 3 lists the sequencing of the optimized mission set.

Table 3. Optimized Mission Set

Mission Phase	Time In Phase
Takeoff/Climb	24 min.
Cruise 1	70 min.
Idle Descent 1	20 min.
Cruise 2	70 min.
Idle Descent 2	20 min
Cruise 3	70 min.
Idle Descent 3	20 min.
Cruise 4	70 min.
Idle Descent 4	20 min.
Shutdown	7 min.
Cooldown	30 min.

Using mission sets instead of single missions, "at-condition" time for major test articles remained the same while fuel consumption for 130 hours at condition (85 missions) dropped from 3,000 gallons to between 700 and 900 gallons. To augment the mission condition changes and to get more test time per day, further enhancements were made to the FSS control system software and safety features to allow unattended operation of the simulator 24 hours around the clock. Prior to this, the system had to be manned as long as it was running, which limited available run time to between 8 and 16 hours per day. By adopting mission sets and utilizing unattended operational capabilities, a 130-hour run could be accomplished in 9 to 10 days instead of 7 or 8 weeks.

EXTENDED DURATION THERMAL STABILITY TEST (EDTST)

The purpose of tests conducted in the EDTST was to supplement the tests of the FSS. The tests on this system were conducted on the same baseline fuel(92-POSF-2926) and blends of PDRA as tested in the FSS (Runs 9 through 18). The heater wetted-wall temperatures and bulk fuel inlet temperature selected for the specific tests were also based on FSS BFA conditions at the high altitude cruise condition. A fuel flow rate of 1 gph was used for the testing in this portion of the program and was selected to allow completion of a 72-hour run with the limited tankage available. A pump outlet pressure of 100 psig was selected to approximately match the FSS BFA inlet pressure. A test duration of 72 hours was used for all of the EDTST runs to approximate the time that the FSS BFA

is at the high altitude cruise condition in 100 total test hours. Since the EDTST heaters do not have quick response, there was no attempt to duplicate the startup and shutdown cycles of the FSS runs.

AUGMENTOR VAPORIZATION FOULING RIG (AVFR)

Test conditions in the AVFR were selected to simulate the conditions typical of an augmentor spray ring or bar. Temperatures were selected such that the maximum tube wall temperature was 1200 °F. The pressure in this appara.' s is essentially atmospheric. The test usually runs for 8 hours each day for a total of about 18 hours run time.

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SECTION 5
EXPERIMENTAL PROCEDURES

This section of the report provides a general description of the procedures used in operating the FSS, EDTST and the AVFR rigs. Through experience gained with each run, some procedures were modified, but these general procedures were followed throughout the program.

REDUCED SCALE FUEL SYSTEM SIMULATOR (FSS)

As described in Section 4, there were two modes of operation of the simulator. Runs 0 through 4 were operated using single standard missions while all remaining runs used mission sets. All of the significant data presented in this report was gathered using mission sets, but the initial runs using the standard mission merit some discussion. This is reserved for Section 8, Discussion of Results.

At the start of a run, the simulator components from the previous run were either cleaned or replaced. Prior to simulator test startup, all tanks were rinsed with baseline fuel. However, if the previous run had been an additive run and the current run was to be a *baseline run*, then all of the tanks were opened and hand-washed with iso-octane and isopropyl alcohol and air-dried to make sure that all of the residual fuel with additive was removed. No attempt was made to replace the tubing between major system components.

In preparation for a new run, once the appropriate components were either cleaned or replaced, approximately 40 gallons of the test fuel was loaded into the conditioning tank and circulated through the conditioning heat exchanger. No heat was applied during this operation. The wing and body tanks were then filled as in a typical mission and then drained. The conditioning tank was then refilled, and fuel was recirculated through the conditioning heat exchanger (again, no heat was applied). The wing and body tanks were then refilled. Fuel was then pumped through the entire simulator to flush out any remaining fuel from the previous test. During this flushing operation, heat was applied to system components to assure proper heater and thermocouple operation and to assure that thermocouple placements were accurate. Bulk fuel temperatures were kept well below 200 °F. Flow, pressure, and differential pressure sensors were also calibrated and monitored for

proper operation. After a couple hours of flushing, the system was drained and made ready for the actual run.

During the initial runs (Runs 0 through 5), heater control for the FCOC and BFA components were operated to maintain a constant temperature rise across the device. In some cases, this resulted in abnormally high wetted-wall temperatures - - especially in the BFA. Upon review, it was determined that a more realistic scenario involved establishing a predetermined temperature in the BFA early in the test and then fixing the heater settings so that heat flux to the BFA remained constant throughout the run. By controlling to a constant differential temperature for the BFA, heat flux into the BFA was constantly rising throughout the run. The only question was whether to set the heater based on BFA external skin temperatures or on BFA internal wetted-wall temperature. Runs 6, 7 and 8 were completed by setting heater output based on BFA external skin temperatures. After further review, it was determined that the most realistic simulation would be to fix the heater settings based on the BFA wetted wall temperature. Runs 9 through 18 were completed in this manner. However, in all runs, the FCOC was controlled based on a fixed temperature rise across the device. This mode was retained for the FCOC because the primary function of the FCOC in these runs was to provide the proper inlet conditions for the BFA and not to act as a primary fouling data point (due to the relatively low temperatures in this device).

For Runs 9 through 18 adjustments were made to heat flux settings to achieve the desired temperature setpoint conditions. Adjustments to control parameters were made as required up through the second full mission set (eighth cycle). All control parameters were "locked in" by the completion of the eighth cycle and no further adjustments were made for the duration of the run. For the remainder of the run, data were gathered and the system was closely monitored to assure proper operation. Since the BFA was being operated with a constant heat flux input, metal temperatures increased during the run. This temperature rise provided the primary method of monitoring the progress of the test. The time to end the run was determined based upon a desired run time and the temperature rise in the BFA. On a couple of occasions, the temperature rise in the BFA was so significant that the run was terminated early (see Section 8). When the test run was completed, the FSS was shut down at the end of a cycle and the system was drained and allowed to cool.

EXTENDED DURATION THERMAL STABILITY TEST (EDTST)

The same basic procedures were utilized for all of the EDTST test runs. The fuel tanks were filled with the test fuel, the system flow (1 gph) and pressure (100 psig) was established. After the flow was stabilized, the heaters were turned on. Due to the slow response of the heaters, their initial settings were established lower than their desired operating temperature. This prevented overshoot of the operating temperatures. When the desired temperatures were reached, the test was declared started. The time from heater startup to the test start was approximately 2 hours. The only heater adjustments made after the test started was to the preheater to maintain a constant fuel temperature at the heater inlet. When the desired test duration was accomplished, the heaters were shut down and the flow maintained until the heaters were cooled. The time to cool the system down was approximately 1 hour.

After the test run with the additive, the system was cleaned before testing with the baseline fuel. The system was cleaned by first flushing with a "Blue Gold" detergent solution. Stoddard solvent (5 gallons) was then used to flush out the detergent solution. Then, the system was flushed for 3 hours with the baseline fuel before the next test run was initiated.

For each test run, the test section tubes were ultrasonically cleaned with an alkaline cleaner (50 % "Blue Gold" cleaner and 50% distilled water). The test section tubes were then rinsed in an ultrasonic cleaner with distilled water and then air-dried. Thermocouples were then spot-welded to the tube surface. The tubes and thermocouples were then installed into the Test Section Assembly.

An air pressurized fuel tank was added to the system after the first test run to provide a backup capability in case of loss of power or a pump failure. This tank is pressurized at a lower pressure (80 psig) than the pump outlet pressure (100 psig). A check valve is installed in the air pressurized tank outlet line to prevent back flow from the pump. System flow was established by use of two valves. A needle valve was set fuel flow to approximately 0.8 gph using the air pressurized tank. An electrically controlled, air driven valve 3metered the additional flow to achieve the desired flow (1 gph) through the system.

AUGMENTOR VAPORIZATION FOULING RIG (AVFR)

The test tube for the AVFR was prepared before each test by soaking it in an alkaline cleaning solution (10% "Blue Gold" in distilled water) in an ultrasonic cleaner. After cleaning, the tube was thoroughly rinsed with distilled water and dried in an oven at 390 °F for 30 minutes. This tube was used in the assembly of the test as described in Section 3.

At the beginning of a run, the heated section of the AVFR tube was purged with nitrogen for about 5 minutes to remove all air. The fuel was also sparged with nitrogen and this sparging was maintained throughout the duration of the run. Fuel flow was then established at the desired value. After several minutes (long enough to fill the heater tube with fuel), the furnace was turned on and controlled to maintain the desired temperature values along the heated tube (usually 1200 °F). A typical test was run about 8 hours a day (including heating time) until the desired test length was achieved. At the end of each day's run, and at the end of the total run, the furnace was turned off and opened for cooling. Fuel flow was maintained for cooling puposes for about 10 minutes or until the maximum tube temperature dropped below 300 °F. At this time, fuel flow was turned off and nitrogen flow was established through the tube until the maximum tube wall temperature was below 100 °F. The tube was then removed, thermocouples were detached and the tube was prepared for carbon burn-off analysis.

SECTION 6
FUEL AND POST-TEST COMPONENT ANALYSIS

This section of the report provides a detailed description of the procedures used in performing results analysis for both the FSS and the EDTST. Of particular interest is the carbon determinations which formed the basis of all quantitative determinations associated with this study.

REDUCED SCALE FUEL SYSTEM SIMULATOR (FSS)

Upon completion of a test run, test articles were removed. Observations indicated typically no deposition in the FCOC areas. Some deposition was noted in the nozzle screen but this amount was not typically quantified since there were no temperature measurements made in this area and it was not an actively heated device. The primary test article was the Burner Feed Arm (BFA). This device was well instrumented and represented the area of prime interest with respect to PDRA performance. For Runs 0 through 4, carbon burn-off capabilities were not available. Deposition in the BFA was determined for these runs by cutting the BFA in half along its length and visually inspecting for deposits. There were a couple of problems with this approach. There were no quantitative results to precisely compare PDRA performance with the baseline fuel and, while deposits were clearly visible to the naked eye, the cutting process caused loss of deposits by knocking them off the metal surface making it impossible to accurately assess deposition along the length of the BFA.

Beginning with Run 5, carbon burn-off analytical capabilities were available and all remaining BFAs from Run 5 through Run 18 were analyzed with this technique. To prepare a BFA for analysis, the BFA was cross-cut into twelve 1-inch segments (see Figure 11). Each segment was prepared in accordance with established procedures (see Appendix A, "Preparation and Analysis of the Burner Feed Arm for the Reduced Scale Fuel System Simulator (FSS)"). Carbon analysis, using a Leco RC-412 Carbon Analyzer, was then run on each segment. Inlet and outlet segments were not considered as part of the data because these areas had fittings on them which were used to connect the BFA to the system. These fittings were not in the heated zone and ,therefore, were not analyzed.

EXTENDED DURATION THERMAL STABILITY TEST (EDTST)

The Test Section tubes are the principal items subjected to post-test evaluations. The test tubes were cut up into 2-inch segments. Each segment was rinsed with heptane, dried in a vacuum oven at 100 °C for 1 hour, and analyzed for carbon using a Leco RC-412 Carbon Analyzer. In order to establish a baseline for blank tubes, a new section of tubing was cleaned using the same pre-test cleaning techniques (see Section 5). The tube was then heated in an oven at 350 °F for 24 hours. It was then cut in segments, cleaned using the normal post-test cleaning techniques, and analyzed for carbon using the Leco RC-412 Carbon Analyzer. An average background carbon for a typical tube has been determined to be approximately 12μg of carbon per cm^2.

AUGMENTOR VAPORIZATION FOULING RIG (AVFR)

Once the augmentor test tube had been removed from the apparatus and the thermocouples had been detached, the outside of the tube was cleaned with sandpaper to remove discoloration and any debris (thermocouple wire, sand, etc.). The tube was then cut into 2-inch sections with a hand-held tubing cutter. These 2-inch sections were rinsed with hexane and dried in a vacuum oven at 212 °F for at least 30 minutes. The sections were then analysed using the Leco RC-412 Carbon Analyzer.

FUEL ANALYSIS

Selected fuel samples were taken throughout this program and submitted for analysis. Fuel specification analyses were accomplished on all baseline fuels used. Samples were periodically drawn of additive blends. These samples were sent to Conoco in Ponca City, Oklahoma, for analysis for additive concentration and shear degradation. The results of all these analyses are presented in Appendix B. In addition to fuel analyses accomplished by Conoco, thermal stability evaluations were accomplished on selected fuel samples using the Jet Fuel Thermal Oxidation Tester (JFTOT) in accordance with ASTM-D-3241. These results are also presented in Appendix B.

SECTION 7
FUEL PREPARATION

This section of the report provides a detailed description of the preparation of the fuels/additive blends used on both the EDTST and FSS for this effort.

Several different fuels were used during this program. The first fuel used was a JP-8 which met all appropriate specifications. However, this fuel was used during the initial runs (Runs 0 through 2) where fuel consumption was very high and the supply of this fuel was soon exhausted. For Run 3, a readily available JP-5 was used, but the supply of this fuel was not large enough to be used for the remaining tests and was exhausted by the completion of Run 8. To complete the testing, 23,000 gallons of Jet-A was purchased and placed in storage in the Building 490 S-Farm. This fuel would be used for the remaining PDRA testing as well as other in-house research. Tables 5 through 7 show the results of specification tests performed on the baseline fuels used in this program.

Blends with PDRA were prepared under the guidance of Conoco. Conoco provided CDR® 102M as a "syrup" blending stock. Concentrations of additive in this blending stock were typically 8,000 to 9,000 parts per million polymer (by weight). Due to the high molecular weight and high viscosity of the Conoco additive, getting the additive uniformly in solution was a formidable task. Great care was taken in every step of the fuel preparation to assure a uniform fuel blend. All additive blends were prepared in the following manner. First, a more dilute blending solution was prepared by placing a calculated amount of PDR blending stock in a 55-gallon drum. Baseline fuel was then added to the drum so that the drum contained a total of about 40 gallons liquid. Second, this blending solution was agitated to assure that the blending stock was completely dissolved. Once the blending solution was prepared, baseline fuel was pumped into a clean, empty tank in the S-Farm. After about 200 gallons of baseline fuel had been pumped into the tank, the blending solution was injected into the incoming flowing fuel stream. The blending solution drum was repeatedly rinsed until all visible traces of the additive were removed. The fuel farm tank was then filled to the appropriate level. Once filled, the additive blend was recirculated for approximately 8 hours. During this recirculation process, fuel was drawn from one end of the underground tank, pumped with a gear

pump through a manifold and back into the opposite end of the tank. This recirculation assured a uniform concentration of additive throughout the tank.

After blending, and during the runs, samples were periodically removed from the tank and the FSS rig itself to assure uniform fuel quality and additive concentrations.

SECTION 8
DISCUSSION OF RESULTS

REDUCED SCALE FUEL SYSTEM SIMULATOR (FSS)

General Discussion:

A total of 19 test runs were completed during this evaluation. Table 4 lists the run conditions for these runs. The evaluation of PDRA was the first test program conducted using the FSS so operating procedures needed to be developed. This was accomplished primarily during Runs 0 through 4. In addition to development of fundamental operating procedures, Runs 0 through 4 provided the opportunity to experiment with various ways of evaluating the test data. No carbon analysis capability existed in-house during these early runs as described in Section 6. Therefore, due to the lack of firm operating procedures and quantitative data analysis, the results of these initial runs, in regards to the PDRA evaluation, are not conclusive. However, some observations were made during these runs that merit some discussion. In Runs 5 through 8, the operating procedures involving the controlling of temperatures in the BFA section were varied to find the most realistic simulation conditions. These variations do not allow direct comparison of Run 0 through 8 data to Runs 9 through 18 data. It was also during Runs 5 through 8 that carbon analysis was first introduced into the test program. After the completion of Run 8, all operating procedures had been "fine-tuned" and these procedures were used for the balance of the program, Runs 9 through 18 These last 10 runs are considered to be most relevant to evaluating PDRA.

Runs 0 through 4:

Runs 0 through 4 mainly involved developing the operating procedures required to conduct the evaluation of the pipeline drag reducer additive in the FSS. Two baseline fuels (an JP-8 and a JP-5) were used because of their availability at the POSF facility. Tables 5 and 6 list the specification test results for these two fuels. Additive blends used were 50 wppm and 15 wppm polymer in these fuels. The BFA section was operated in a mode where the bulk fuel temperature rise across the BFA was fixed for the duration of the run, which was 85 missions. Both additive and baseline fuels were evaluated. Since carbon analysis was not available for these runs, the BFA tubes were cut in half lengthwise for visual inspection of deposits. Figures 18 and 19 show deposition on the inner

TABLE 4. - SUMMARY OF FSS RUN CONDITIONS

Run No.	*Fuel Name*	*Additive Conc. (wppm)*	*Run Hours*	*Segm't #7 Wall Temp °F*	*Notes*
0	JP-8 Baseline	0	130	~470*	85 Single Missions
1	JP-8 with PDRA	50	130	~470*	85 Single Missions
2	JP-8 with PDRA	50	130	~470*	85 Single Missions
3	JP-5 with PDRA	15	130	~470*	85 Single Missions
4	JP-5 Baseline	0	130	~470*	85 Single Missions
5	JP-5 Baseline	0	130	~470*	BFA controlled based on fixed outer wall temperature. See Section 5.
6	JP-5 Baseline	0	122	475	
7	JP-5 with PDRA	15	132	475	
8	JP-5 with PDRA	15	130	475	
9	Jet-A Baseline	0	78.5	475	
10	Jet-A Baseline	0	94.4	450	
11	Jet-A with PDRA	15	96	450	These fuel blends are subject to question
12	Jet-A with PDRA	15	65.7	475	
13	Jet-A Baseline	0	69.6	475	
14	Jet-A with PDRA	15	76	475	
15	Jet-A with PDRA	15	100	450	
16	Jet-A Baseline	0	98.2	420	
17	Jet-A with PDRA	15	72	420	
18	Jet-A Baseline	0	72.3	420	

** Approximate temperature based upon fixed temperature rise across BFA, see Section V.*

BFA surfaces for the Baseline JP-8 and the Baseline JP8+ 50 wppm CDR®102M polymer, respectively. Figures 20 and 21 show deposition on the inner BFA surfaces for the Baseline JP-5 and the Baseline JP5+ 15 wppm CDR®102M polymer, respectively. During all runs, the initial BFA wetted-wall temperatures were between 480 and 500 °F, depending on the phase of the mission. As can be seen in the photographs, for the JP-8, there was significantly more deposition with the additive than without. For the JP-5, deposition was approximately the same with and without the additive.

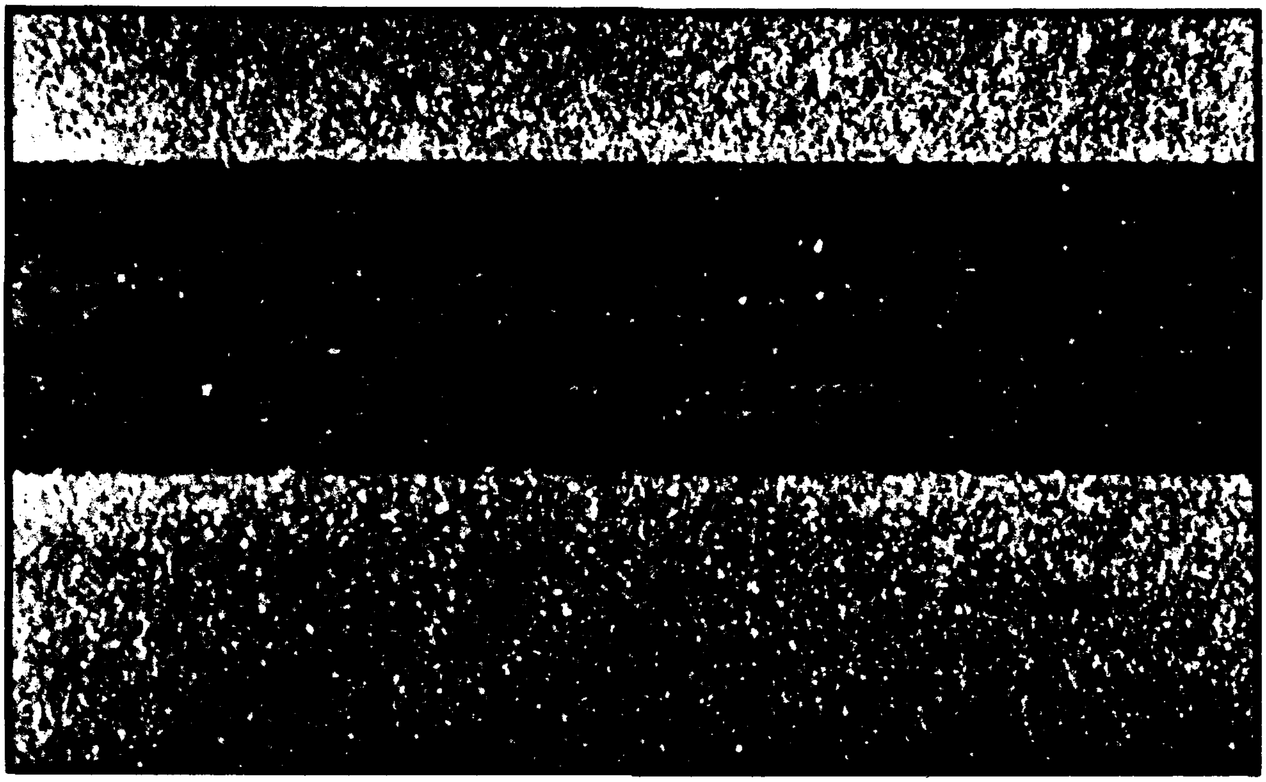

Figure 18 - BFA Deposition,Run 0, JP-8 Baseline

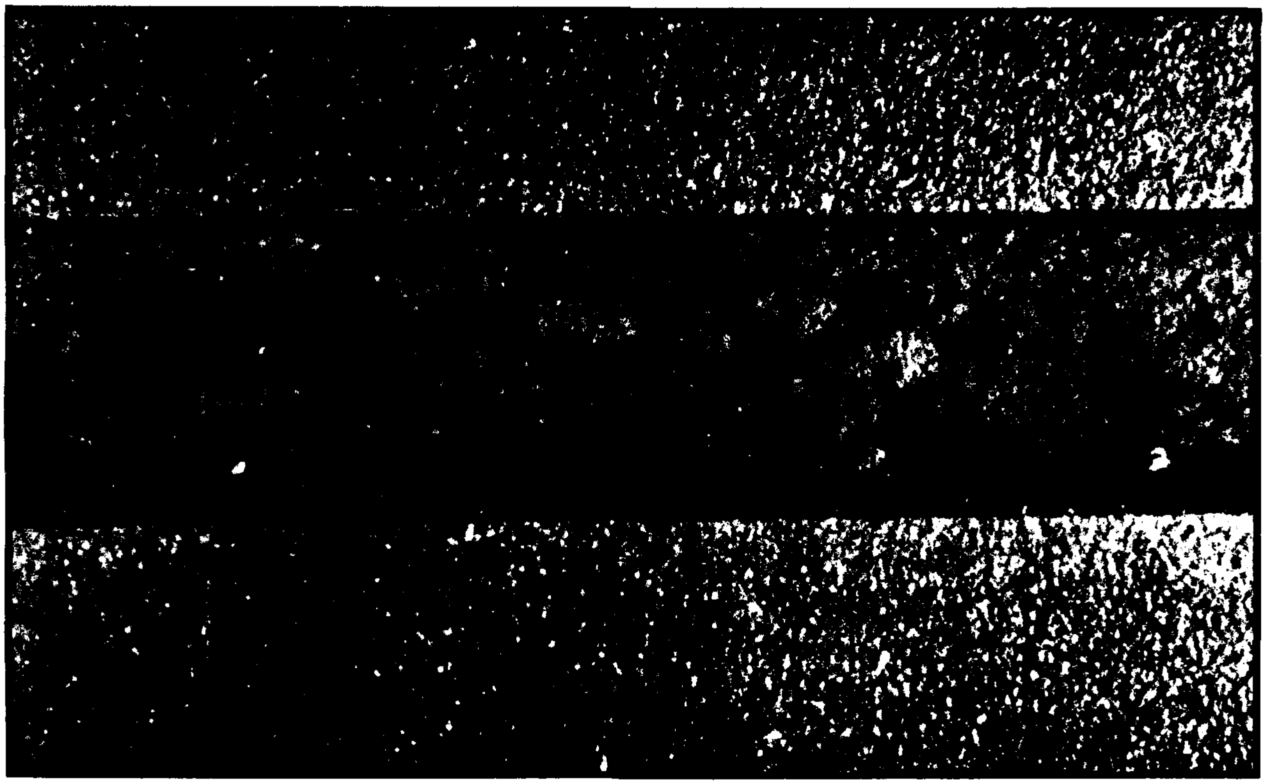

Figure 19 - BFA Deposition,Run 2, JP-8 + 50 wppm PDRA

Figure 20 - BFA Deposition, Run 4, Baseline JP-5

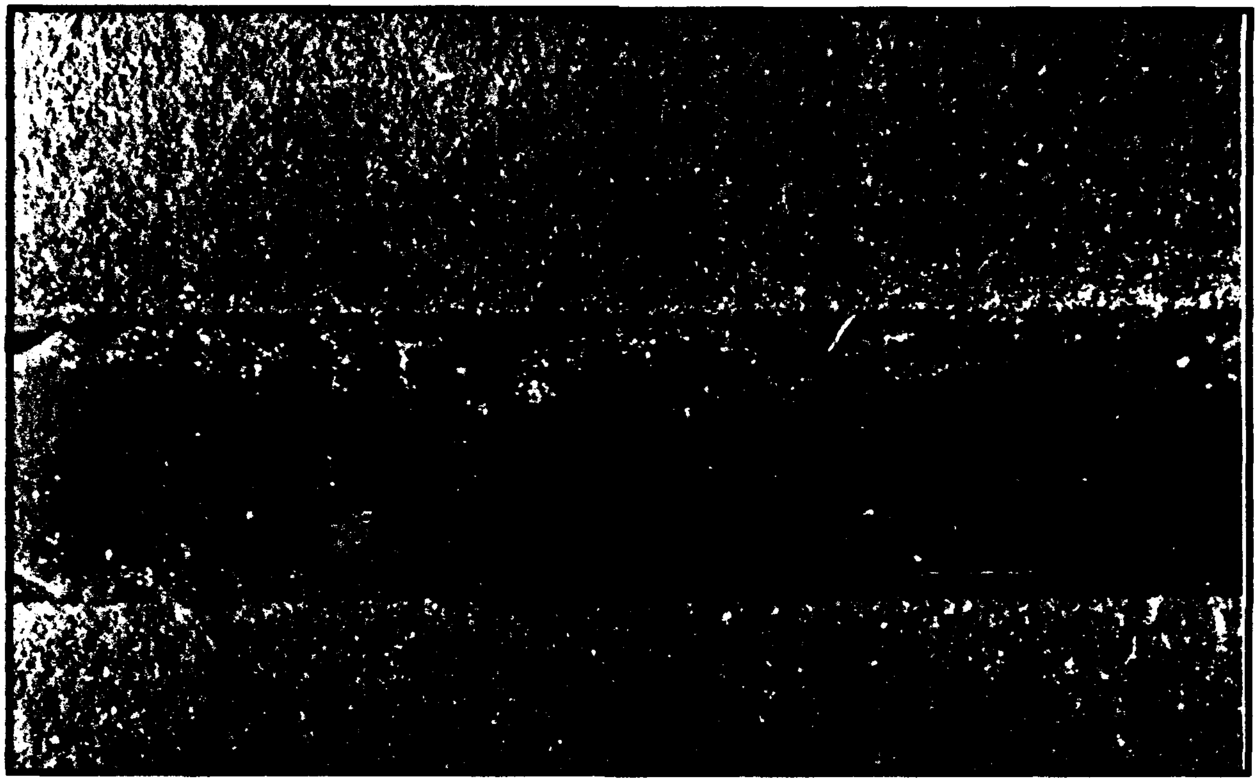

Figure 21 - BFA Deposition, Run 3, JP-5 + 15 wppm PDRA

TABLE 5. - SPECIFICATION TEST RESULTS - JP-8

ASTM Method	Test	Results
D156	Color, Saybolt	+12
D3242	Total Acid Number, mgKOH/g	0.011
D1319	Aromatics, Vol%	19.6
D1319	Olefins, Vol%	1.6
D3227	Mercaptan Sulfur, wt%	0
D2622	Sulfur, Total, wt%	0
D2887	Distillation, Initial Boiling Point, °C	130
D2887	Distillation, Endpoint, °C	293
D1298	Density, kg/liter	0.814
D93	Flashpoint, °C (°F)	61(142)
D2386	Freeze Point, °C (°F)	-49(-56)
D130	Copper Strip Corrosion	1b
D3241	Thermal Stability @ 260 °C, Delta P, mmHg	0
D3241	Thermal Stability @ 260 °C, Tube Code	1
D3241	Thermal Stability @ 260 °C, TDR Rating	1
D381	Existent Gum, mg/100ml	0.8
D2276	Particulate Matter. mg/liter	0.4
SPEC	Filtration Time, minutes	14
M5340	Fuel System Icing Inhibitor, Vol%	0.10

Runs 5 through 8:

For these runs, the fundamental procedures developed in Runs 0 through 4 were maintained. Run 5 was operated with the same procedures as in Runs 0 through 4. However, the BFA heat input control was varied starting with Run 6 to determine the most effective control mode for this component. Instead of controlling the BFA based upon bulk fuel temperature rise, four thermocouples were placed on the BFA at the exterior surface (of what would now be Segments 4 and 7, see Figure 11). The heat input to the BFA was then controlled to maintain the mathematical average of the two middle thermocouple temperatures. An average surface temperature was established

TABLE 6 - SPECIFICATION TEST RESULTS - JP-5

ASTM Method	Test	Results
D156	Color, Saybolt	+15
D3242	Total Acid Number, mgKOH/g	0.009
D1319	Aromatics, Vol%	17.0
D1319	Olefins, Vol%	2.9
D3227	Mercaptan Sulfur, wt%	0.001
D2622	Sulfur, Total, wt%	0.04
D2887	Distillation, Initial Boiling Point, °C	132
D2887	Distillation, Endpoint, °C	279
D1298	Density, kg/liter	0.818
D93	Flashpoint, °C (°F)	66(151)
D2386	Freeze Point, °C (°F)	-49(-56)
D130	Copper Strip Corrosion	1a
D3241	Thermal Stability @ 260 °C, Delta P, mmHg	0
D3241	Thermal Stability @ 260 °C, Tube Code	1
D3241	Thermal Stability @ 260 °C, TDR Rating	Nor Reported
D381	Existent Gum, mg/100ml	2.2
D2276	Particulate Matter. mg/liter	0.4
SPEC	Filtration Time, minutes	8
M5340	Fuel System Icing Inhibitor, Vol%	0.12

such that the same internal wetted-wall temperatures of earlier runs was obtained. The exception to this is Run 5 which was run with the BFA still controlled based on bulk fuel temperature rise.

In addition, the concentration of the PDR additive used was reevaluated. It was determined that it would be unlikely for more than three to five additive injections to occur in a pipeline system, with each injection adding between 2 and 3 wppm polymer to the pipeline material. Therefore, additive concentrations were limited to 15 wppm. It was also during these runs that operation of the FSS using single missions was abandoned and mission sets were implemented. Unattended operation was not implemented until Run 12.

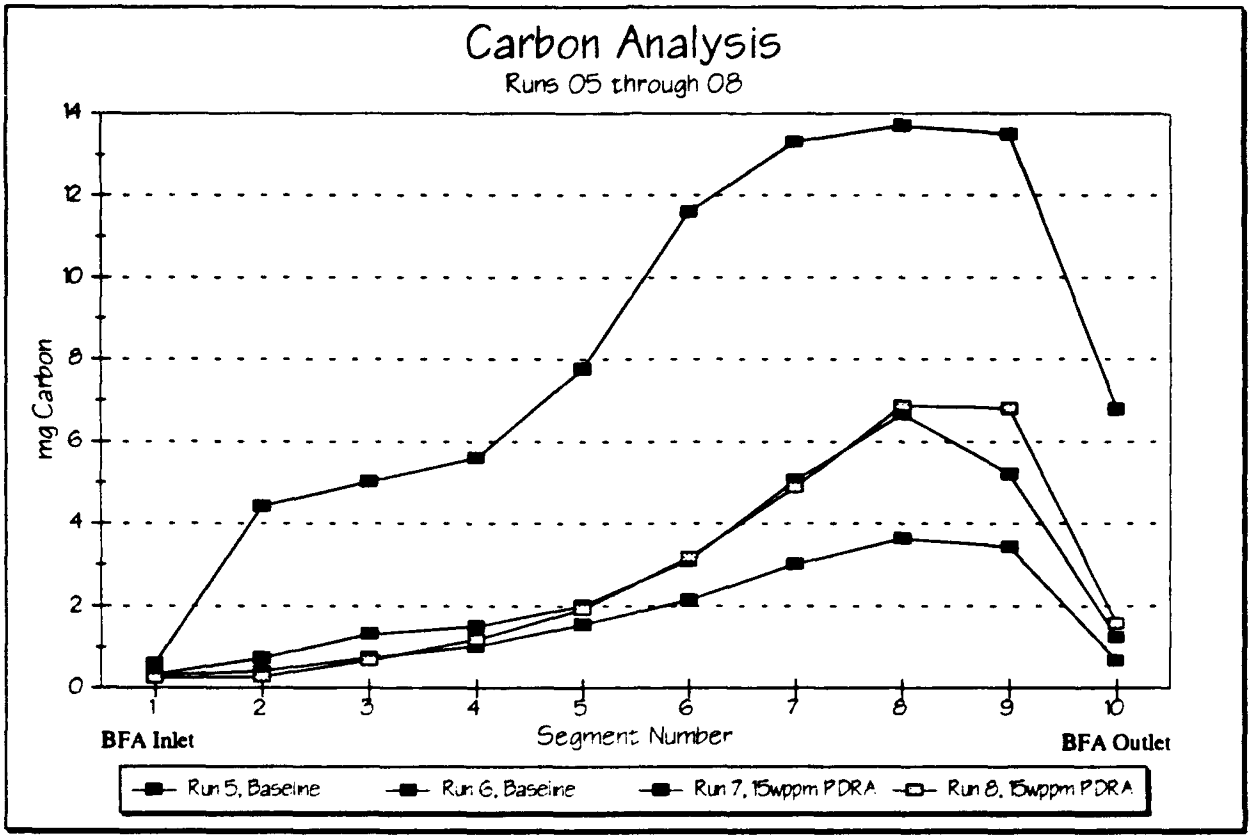

Figure 22 - BFA Carbon Analysis Profiles, Runs 5-8

Runs 5 and 8 were operated for 130 at-condition hours while Run 6 ran 122 hours and Run 7 ran 132 hours. At the completion of each run, the BFA tube was cut into twelve 1-inch segments and analyzed for carbon deposition using a Leco RC-412 Carbon Analyzer. The results of these analyses are presented in Figures 22 and 23. Figure 22 shows the amount of carbon deposited in each segment, in terms of mg (milligrams). Figure 23 shows the deposition rate for each of the four runs in terms of mi ›grams carbon per centimeter squared per hour ($\mu g/cm^2hr$). This offers a better comparison of the data since all four runs were not for the same duration. These figures show how operation of the BFA using a constant bulk fuel temperature rise differs from using an averaged constant skin temperature. This data (from Runs 6,7 and 8) indicated that there may be no significant impact in fuel thermal stability by the PDR additive. However, since the exact history of the JP-5 being used was uncertain, it could not be determined if these results reflected true additive effects

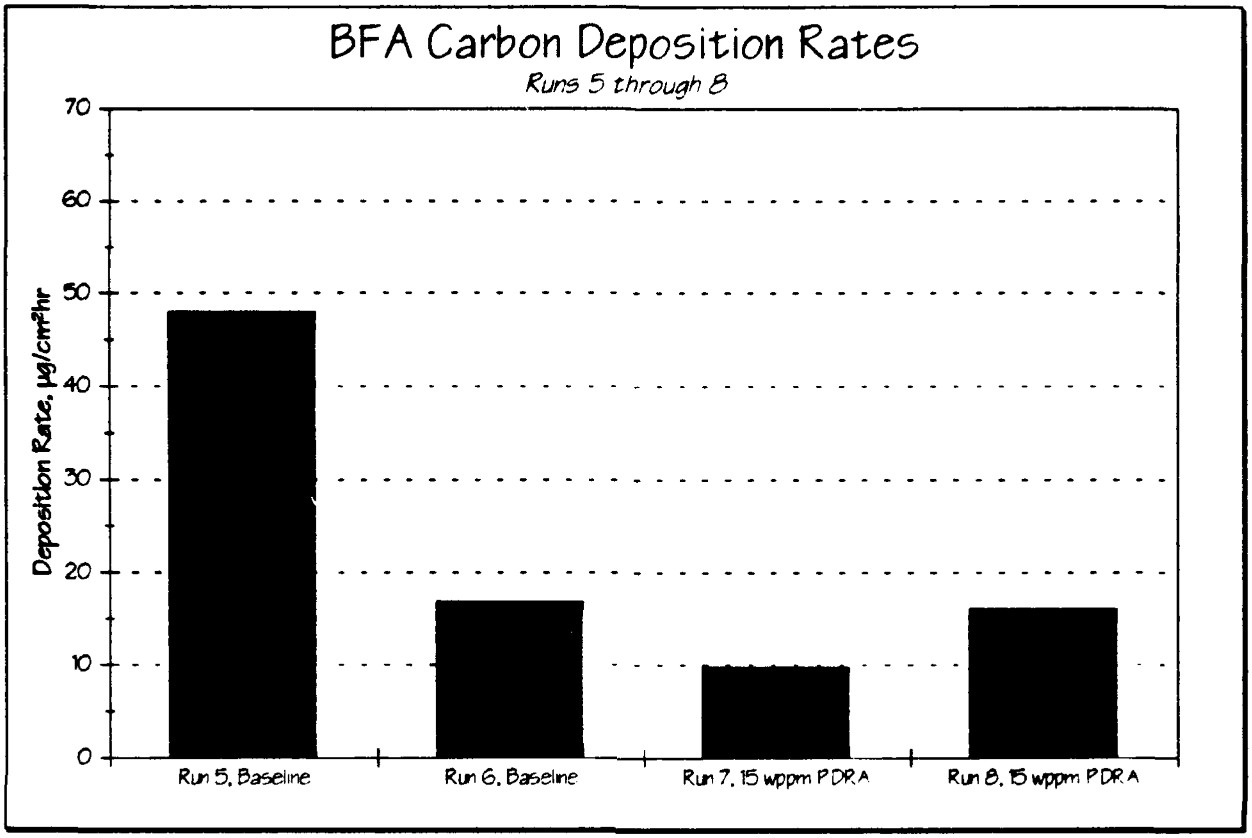

Figure 23 - BFA Total Carbon Deposition Profiles, Runs 5-8

or some other unknown affect. It was, therefore, decided that a new supply of fuel would be purchased for the remainder of the test program.

It was also determined that the actual heat flux being applied to the BFA was decreasing throughout each test run because the heater was being controlled based on maintaining an average BFA outer skin temperature. As deposits built up on the internal BFA surface, the fuel became insulated from the hot tube wall. This caused the heat transfer into the fuel to decrease, resulting in a rise in outer skin temperature. In response to this temperature rise, the heaters would cut back to maintain a constant average skin temperature. This did not simulate the thermal heating of nozzles and burner feed arms as occurs in actual engines. Also, since the controlling thermocouples were on the exterior skin and this surface could not be insulated due to their proximity to the RF heater coils, it was uncertain if heat loss to the environment might be causing some problems and resulting in false

control points. It was, therefore, determined that a constant heat flux to the BFA would be used for the remainder of the program.

Runs 9 through 18:

A new fuel supply was introduced beginning with Run 9. Previous runs had depleted the in-house fuel supplies so a fresh supply of 23,000 gallons of Jet-A was purchased. This supply would be sufficient to complete this and other programs. Table 7 shows specification test results for this new fuel sample (92-POSF-2926). As shown in this table, the fuel met or exceeded all specification requirements.

TABLE 7 - SPECIFICATION TEST RESULTS - Jet-A Fuel, 92-POSF-2926

ASTM Method	Test	Results
D156	Color, Saybolt	Not Reported
D3242	Total Acid Number, mgKOH/g	0.002
D1319	Aromatics, Vol%	22
D1319	Olefins, Vol%	Not Reported
D3227	Mercaptan Sulfur, wt%	0.001
D2622	Sulfur, Total, wt%	0.1
D2887	Distillation, Initial Boiling Point, °C	Not Reported
D2887	Distillation, Endpoint, °C	264
D1298	Density, kg/liter	0.811
D93	Flashpoint, °C (°F)	Not Reported
D2386	Freeze Point, °C (°F)	-43(-45)
D130	Copper Strip Corrosion	1b
D3241	Thermal Stability @ 260 °C, Delta P, mmHg	0
D3241	Thermal Stability @ 260 °C, Tube Code	1
D3241	Thermal Stability @ 260 °C, TDR Rating	Not Reported
D381	Existent Gum, mg/100ml	2.0
D2276	Particulate Matter. mg/liter	0.1
SPEC	Filtration Time, minutes	Not Reported
M5340	Fuel System Icing Inhibitor, Vol%	0

A final reassessment of the BFA design was completed and some changes were made to the mode of operation and to the placement of thermocouples. The number of thermocouples used to measure wetted-wall temperatures was increased from 4 to 10, placing one at the midpoint of each 1-inch segment in the heated zones. The four thermocouples placed on the exterior of the BFA for measuring skin temperature for Runs 5 through 8 were retained. This thermocouple arrangement is depicted in Figure 11 and was maintained for the remainder of the test program. In addition to increasing the number of thermocouples, the heat flux to the BFA was set by establishing the desired hot-spot wetted-wall temperature and fixing the heater output to maintain this value. Since at high temperatures, fouling can initiate almost immediately, the desired heat rate was established early in the test before significant deposition resulted. This was the mode adopted and maintained for the remainder of the program.

Throughout runs 0 through 8, it had been noted that beginning around 20 to 30 hours (at condition), fouling could be detected simply by observing the temperature rise in selected BFA thermocouples. It was reasoned that if fouling could be detected this early, there was probably no use in running a full 130 hours - - perhaps enough data could be gathered in around 80 hours and thereby save fuel and run time. It was, therefore, decided that future runs would be long enough to obtain significant deposition without allowing the wetted-wall temperatures to get too high. Deposition was monitored based on BFA wetted-wall temperature rise.

Run 9 was the first run with the new Jet A fuel (92-POSF-2926) and using the revised BFA temperature control procedures. A hot spot temperature of 475 °F was selected for this run based on information received from nozzle manufacturers concerning actual operating temperatures. It was anticipated that this hot spot temperature would occur at the same point as measured in previous tests. However, since more thermocouples were now installed on the BFA, we discovered that the actual hot spot was 2 inches downstream of where it had presumably been. Therefore, it was determined that BFA heater control would be based upon the pseudo-hot spot location as determined in Runs 0 through 8 in order to provide comparisons between the new runs and Runs 0 through 8. This pseudo-hot-spot temperature was located at thermocouple location TE53 in Segment 7 (see Figure 11). The actual hot spot temperature at thermocouple location TE55, Segment 9 would be

monitored and recorded. It turned out that the TE55 temperature was some 10 degrees higher than TE53 while TE53 was in the range of 475 °F. In lower temperature ranges, the difference was less.

Run 9 proceeded normally until about 40 hours into the test. A severe thunderstorm occurred in the area resulting in a power outage to all of the facilities in the Fuels and Lubrication Division. During this power outage, BFA temperatures climbed quickly because of the mass of the BFA tube and the lack of fuel flow through it. Upon restart of the test, the temperature profile of the BFA had shifted down about 10 to 15°F. This was most likely due to heavy fouling inside the BFA which was then flushed away upon test restart. Temperature profile and carbon analysis data are shown in Appendix C.

Run 10 was a duplicate of Run 9 except that the TE53 temperature was targeted to be 450 °F with TE55 being 456 °F. The baseline Jet-A (2926) was used. Run 10 proceeded well until an operator error resulted in an abrupt system shutdown. Recovery, however, was quick and there was no apparent effect on the data. Run 10 was terminated after 94.4 hours. This run time was longer than for Run 9 because the 80-hour point occurred during the weekend. The run was extended to a working day to avoid having to do shutdown and disassembly on the weekend. Temperature profile and carbon analysis data are shown in Appendix C.

Run 11 was intended to be a duplicate of Run 10, only with 15 wppm additive. To prepare the additive blend, 0.17 lbm of polymer was added to 1672 gallons of Jet-A to formulate a blend that was 15.07 wppm polymer. This blend would be used for both Runs 11 and 12. It was also during this run that unattended operations became the standard mode of operation. Temperature profile and carbon analysis data are shown in Appendix C.

Run 12 was a duplicate of Run 9 except the same additive blend was used that was used in Run 11. The apparent deposition rate in this run was extremely high such that hot-spot wetted-wall temperatures exceeded 565 °F in just over 65 test hours. It was decided to terminate the run at this time. Later carbon deposition analysis would yield results that were not in line with the temperature rise observed at TE53 and TE55. It was assumed that the EDM cutting process caused deposit loss - - probably due to the deposit thickness (as indicated by the sharp temperature rise of the wetted-wall). Temperature profile and carbon analysis data are shown in Appendix C.

With Run 9 having suffered a shutdown and possible adverse fouling conditions and with the rapid, unexpected apparent fouling that occurred in Run 12, another attempt was made at the Run 9/Run 12 conditions. This run functioned properly with the exception of the thermocouple TE55. It was reading higher than normal temperatures as compared to the TE53 temperature and the profiles of Runs 9 and 12. It was decided to ignore this TE55 temperature because it was probably due to improper insertion of the thermocouple into the BFA. This was later verified upon disassembly of the BFA. Again, rapid fouling occurred such that TE53 exceeded 590 °F in 70 hours. Therefore, the run was terminated at 70 hours. Temperature profile and carbon analysis data are shown in Appendix C.

Run 14 is essentially a rerun of Run 12. This run was made to provide duplicate data at the Run 12 conditions. Because previous additive runs had consumed nearly all of the blended fuel, and EDTST results indicated there might be a problem with the fuel/additive blend, a new blend of PDR additive in Jet-A was prepared. The resultant concentration of PDR additive for the new blend was 14.87 wppm polymer. A total of 2277 gallons of this blend was prepared. Wetted-wall temperatures indicated that rapid deposition was occurring. The run was terminate at 76 hours. Temperature profile and carbon analysis data are shown in Appendix C.

Run 15 was a duplicate of Run 11 with TE53 being controlled to 450 °F. Total test duration was 100 hours at which time the test was terminated. The test functioned normally and the apparent deposition rate, as indicated by wall temperatures, was significantly less than for the higher temperature cases (Runs 12 and 14). Temperature profile and carbon analysis data are shown in Appendix C.

Runs 9 through 15 evaluated the effects of PDR additive based upon a range of realistic temperatures. The question remained, however, concerning how this additive would affect components operating well below 450 °F. Therefore, Runs 16 through 18 were accomplished with hot spot temperatures at 420 °F. The baseline conditions were duplicated to assure meaningful data. Runs 16 and 18 were the baseline runs with Run 16 being for 100 hours and Run 18 being for 72 hours. Run 17 was the additive run and used the same fuel blend as Runs 14 and 15. Temperature profile and carbon analysis data are shown in Appendix C.

FSS Run Comparisons:

Comparisons of the various runs are made based upon hot spot wetted-wall temperature. The baseline fuel runs at 420 °F were runs 16 and 18. The additive run at this temperature was Run 17. Figure 24 shows the temperature profiles for TE53 for Runs 16 through 18.

Figure 24 shows that at lower wetted-wall temperatures, the performance of the fuel with PDR additive is not significantly different from the baseline fuel. Figure 25 shows the carbon deposition profile for these same runs. This figure also shows that the performance of fuel with PDRA is not significantly different from the baseline fuel at these low temperatures.

Runs 10, 11 and 15 were completed with a wetted-wall hot spot temperature of 450 °F. At these temperatures, the differences in performance between the baseline fuel and the fuel with PDR additive becomes apparent. Figure 26 illustrates the BFA temperature profile for additive and baseline fuels at a wetted wall hot spot temperature of 450 °F. The temperature rise experienced for the additive fuel (Run 15) was significantly higher than for the baseline run (Run 10). Run 11 performance, however, was very close to the baseline performance. This was probably a fuel-related problem. As will be seen in the discussion on the EDTST results, there was some question as to the integrity of the fuel/additive blend that was used for Runs 11 and 12. It is probable that the fuel was not blended completely which resulted in lower-than-expected additive concentrations. The fuel/additive blend used in Run 15 was a separate blend from that used in Run 11. Figure 27 shows the carbon deposition profile for Runs 10, 11 and 15. Here again, the performance of Run 11 was more like the baseline fuel performance. If the fuel blend for Run #11 was indeed faulty, then Figure 27 shows that deposition at the hot spot for additive fuel is over 350% higher than for the baseline fuel at the same temperature.

Runs 9, 12, 13, and 14 were conducted at an initial wetted wall hot spot of 475 °F. The performance differences between additive and baseline fuels is just as marked at this temperature as it was at 450°F. Figure 28 shows the temperature profiles for the BFA for these runs. The drop in the line for Run 9 indicating the power outage caused by a thunderstorm can clearly be seen. This power outage invalidated this run. It must also be noted that the fuel blend used for Run 12 was part of the same batch that may have been blended improperly as described earlier. This explains why the

additive performance in Run 12 is similar to the baseline fuel performance. If Runs 9 and 12 are not considered for these reasons, then it can be seen from Figure 28 that the additive blend resulted in higher temperatures in the BFA during the test. Figure 29 shows the carbon deposition profile along the tube for these runs. Again, discounting Runs 9 and 12 for the reasons just mentioned, Figure 29 shows that deposition in the additive blend is significantly greater than for the baseline fuel, as much as more than 350% greater at the hot spot. To summarize, Table 8 presents the total carbon deposited on the BFA for each of the Runs 9 through 18 as well as the time averaged deposition rate for these runs. This table shows that for temperatures of 450 °F and higher, the PDR additive appears to have a detrimental effect on fuel thermal stability.

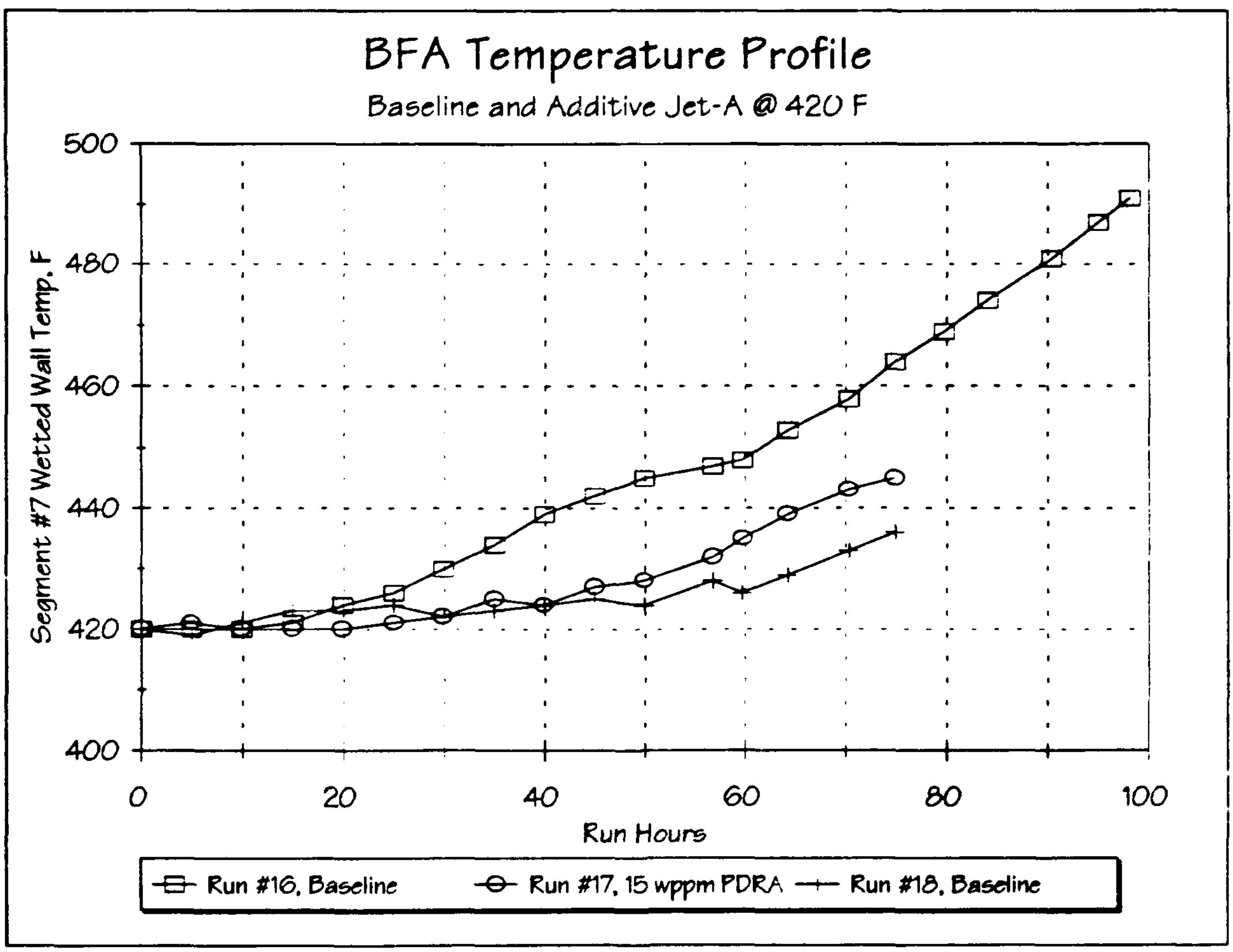

Figure 24 - BFA Temperature Profile, 420 °F

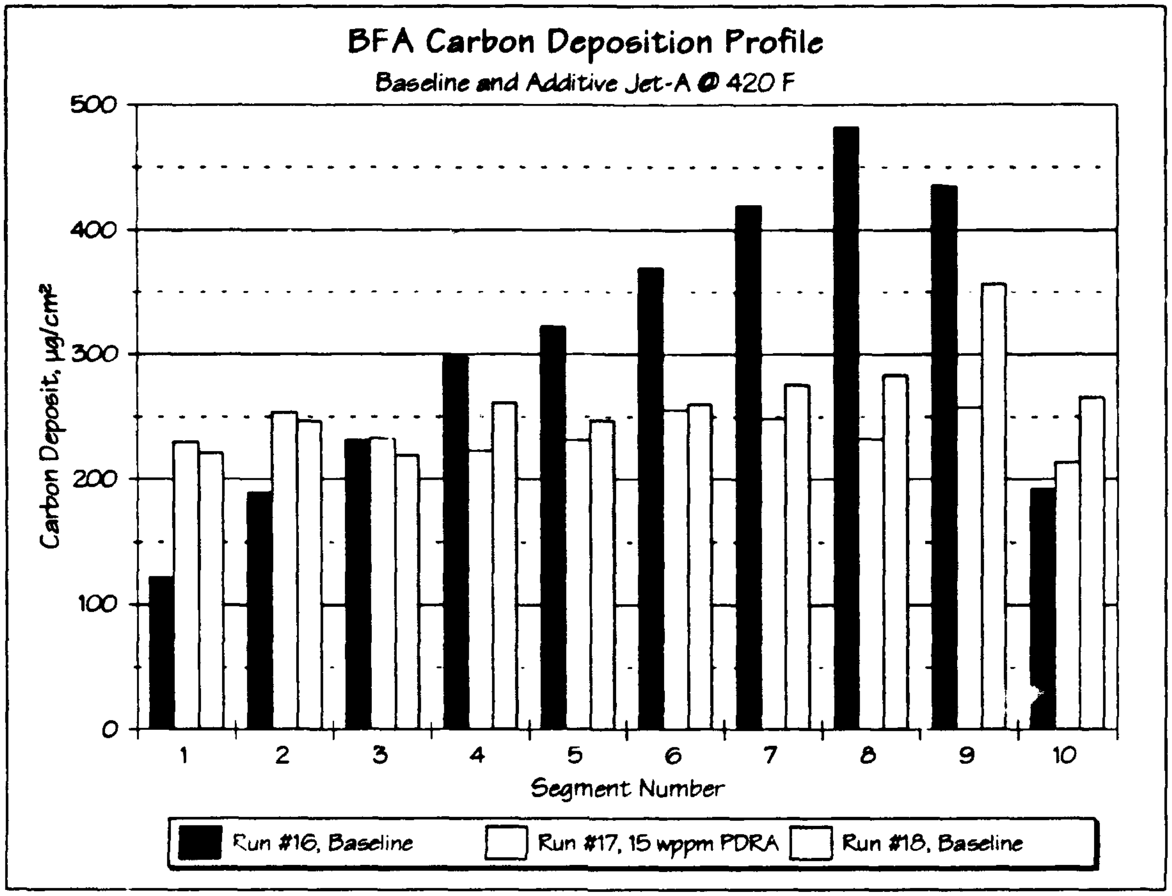

Figure 25 - BFA Carbon Deposition Profile, 420 °F

TABLE 8 - BFA Carbon Analysis Results, Total Carbon Deposited

Temp (°F)	FSS Run No.	Total Carbon Deposited (µg/cm^2)	Carbon Deposition (µg/cm^{2}hr)	Additive or Baseline	Comments
420	16	305.6	3.112	Baseline	
	17	237.4	3.297	Additive	
	18	263.2	3.641	Baseline	
450	10	276.5	3.638	Baseline	
	11	317.0	4.171	Additive	Questionable Blend
	15	766.0	7.66	Additive	
475	9	753.0	9.908	Baseline	Power Outage, Over-temp
	12	230.6	3.034	Additive	Questionable Blend
	13	436.6	5.745	Baseline	
	14	836.2	11.0	Additive	

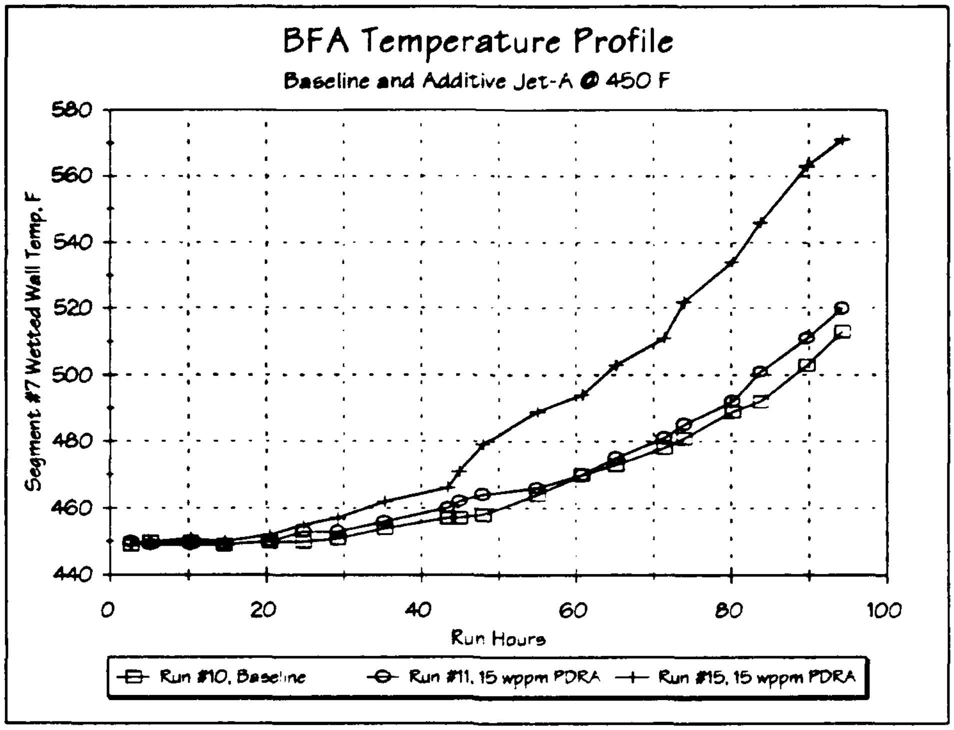

Figure 26 - BFA Temperature Profile, 450 °F

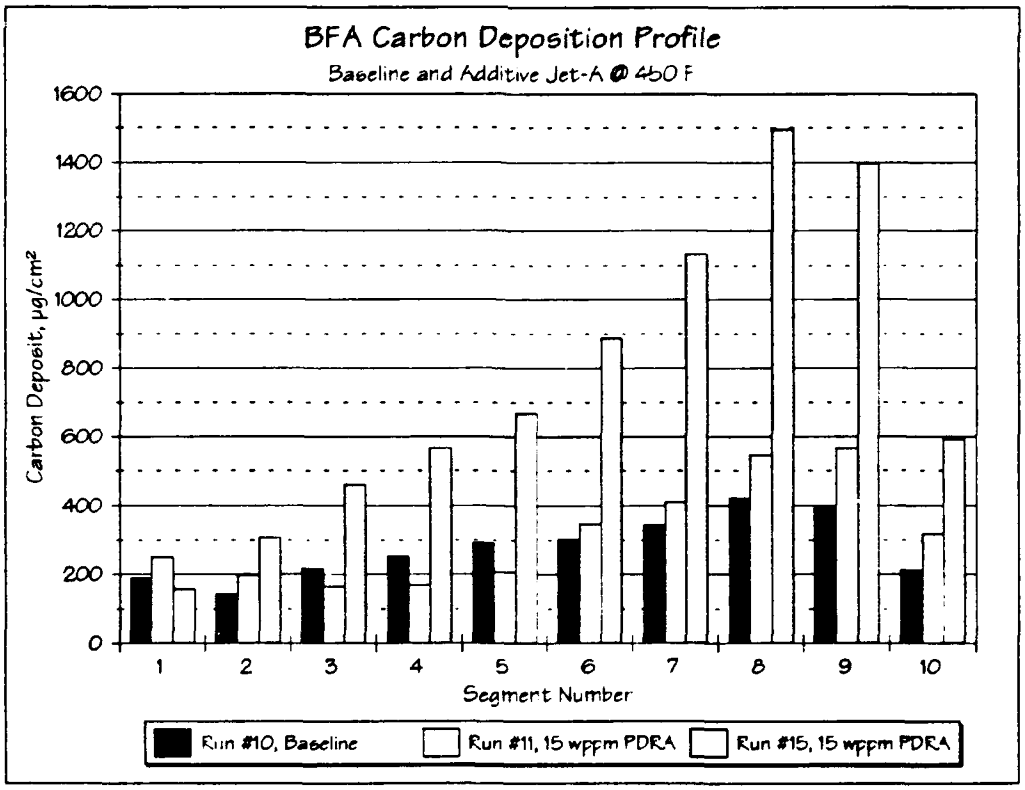

Figure 27 - BFA Carbon Deposition Profile, 450 °F

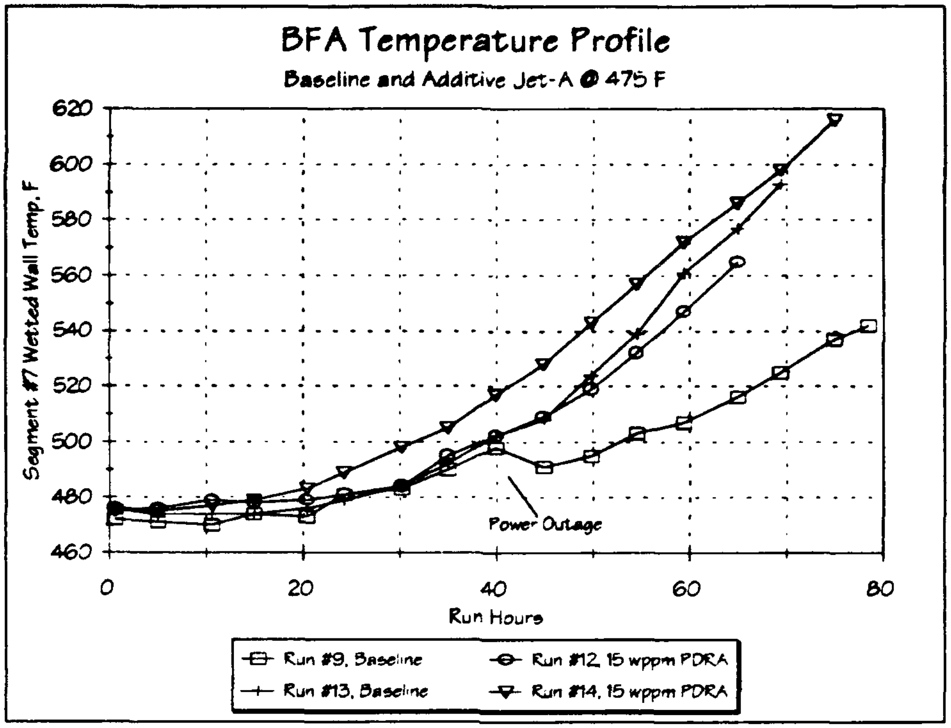

Figure 28 - BFA Temperature Profile, 475 °F

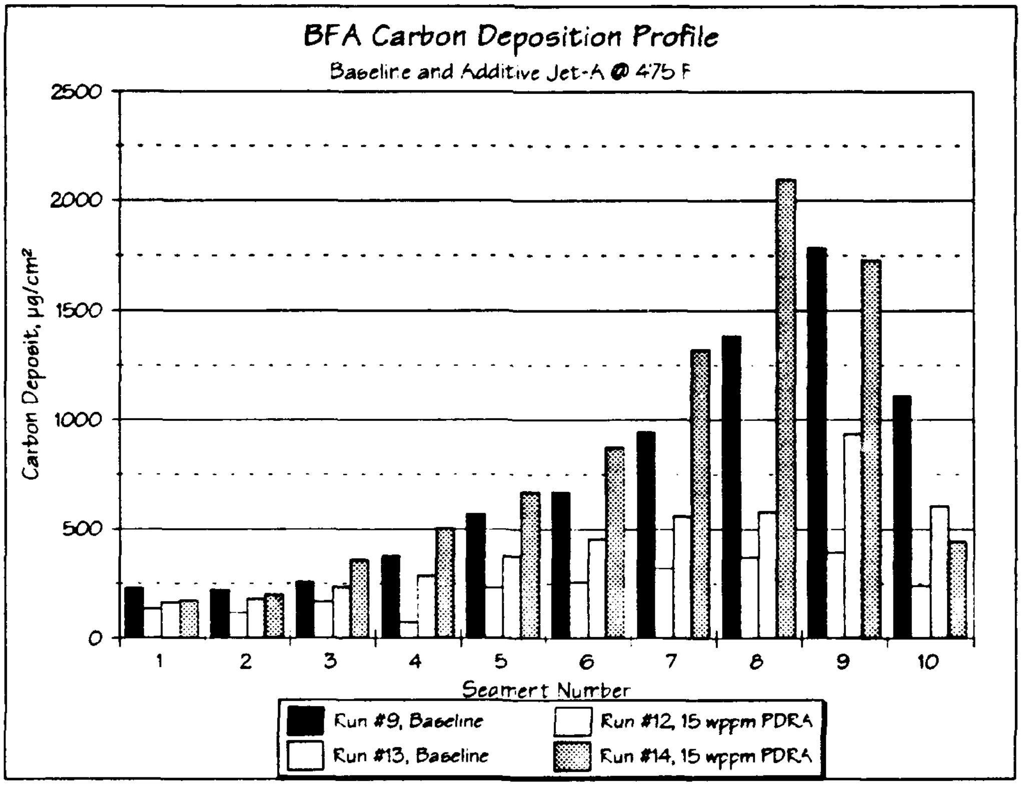

Figure 29 - BFA Carbon Deposition Profile, 475 °F

EXTENDED DURATION THERMAL STABILITY TEST (EDTST)

These were the initial runs of this system after the modification discussed in Section 3. Therefore, the goals of this first series of tests were to determine the feasibility of using the EDTST system for fuel thermal stability research and to verify and/or supplement the FSS evaluation of PDRA with data obtained by the EDTST.

Several test runs were completed during this investigation. EDTST Run 1 was a test on the baseline fuel (92-POSF-2926) at a heater test section maximum wetted-wall temperature of 460 °F. EDTST Run 2 was a repeat of Run 1 except a maximum heater test section wetted-wall temperature of 450 °F was used. EDTST Run 3 was a repeat of Run 2 except a fuel blend with 15 wppm PDR additive was used. EDTST Run 4 was a complete repeat of Run 3. EDTST Run 5 was also a repeat of Run 3.

All of the EDTST runs were conducted 72 hours in duration with 92-POSF-2926 (Jet-A) used as the baseline fuel. The goal of EDTST Run 1 was basically to checkout the system and to determine the minimum temperature threshold for forming carbon deposits with the baseline fuel. It was conducted at a lower temperature (460 °F) than the initial RSS test runs to provide information about this threshold. Based on the results of this test, 450 °F was selected as one of the baseline temperatures for conducting comparison tests on the baseline fuel with and without PDRA in both the FSS and EDTST. Run 1 verified that the desired heat inputs and fuel flow could be maintained with this system and established a basis for temperature comparisons for future testing.

After completion of this initial run, the 1/8-inch heater test section tube was cut in 1-inch-long segments. These segments were then analyzed for carbon in the Leco RC-412 Carbon Analyser. The results of these analyses indicated that there was carbon deposition on the tubes, but the amount was quite small. It was, therefore, decided that 2-inch-long segments would be used in future tests.

The Leco carbon analysis results from EDTST Runs 2-5 are shown in Figures 30, 31 and 32. EDTST Run 2 results are included in all the figures to provide a basis for comparison. As can be observed in the these figures, the amount of carbon deposit appeared to become progressively smaller for each additive fuel test (Runs 3, 4 and 5). The total carbon deposits in the heated test section also

decreased as the tests progressed as shown in Figure 33. It is suspected that reduced amounts of the additive were present in the test fuel for the last two tests. These results agreed with the results of the FSS tests as discussed previously in this Section. It was, therefore, decided to blend another mixture of the baseline fuel and the additive for additional tests to verify this additive depletion and to complete the evaluation of PDRA.

A new blend of fuel with the additive was tested at wetted-wall temperatures of 450 °F and 480 °F, respectively, (EDTST Runs 6,8 and 9). EDTST Run 6 was a test of the baseline fuel at 480 °F heater test section tube maximum wetted-wall temperature. EDTST Run 8 was a test of the baseline fuel with 15 ppm PDRA and a heater test section tube maximum wetted-wall temperature of 480 °F. EDTST Run 9 was the same as Run 8 except with a heater test section tube maximum

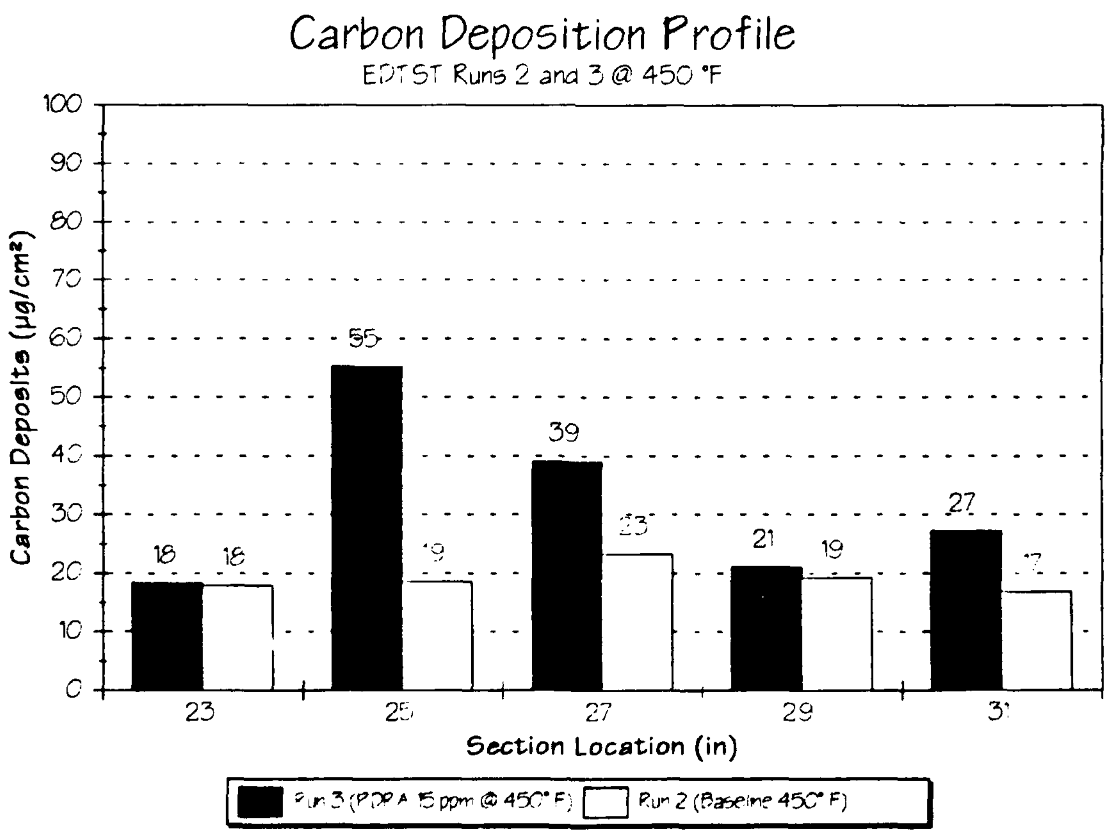

Figure 30 - EDTST Runs 2 and 3 Deposition Profile, 450 °F

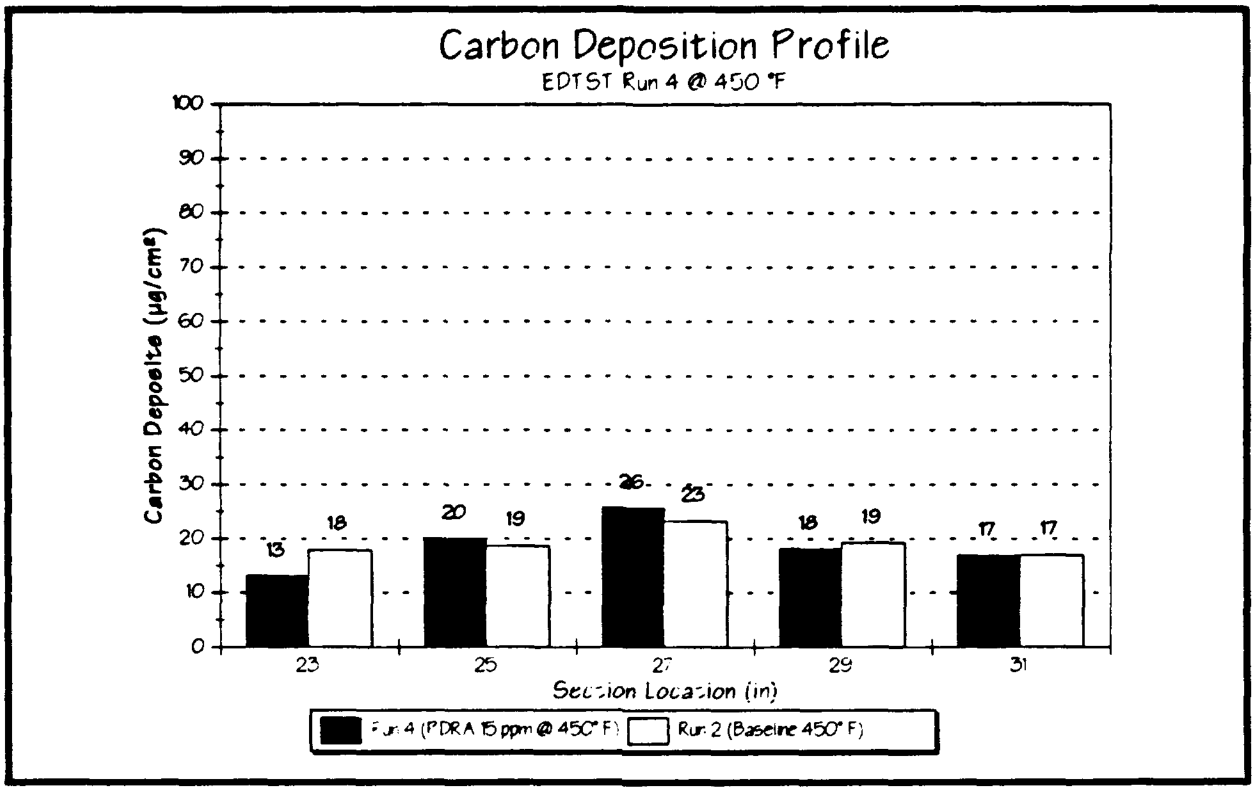

Figure 31 - EDTST Runs 2 and 4 Deposition Profile, 450°F

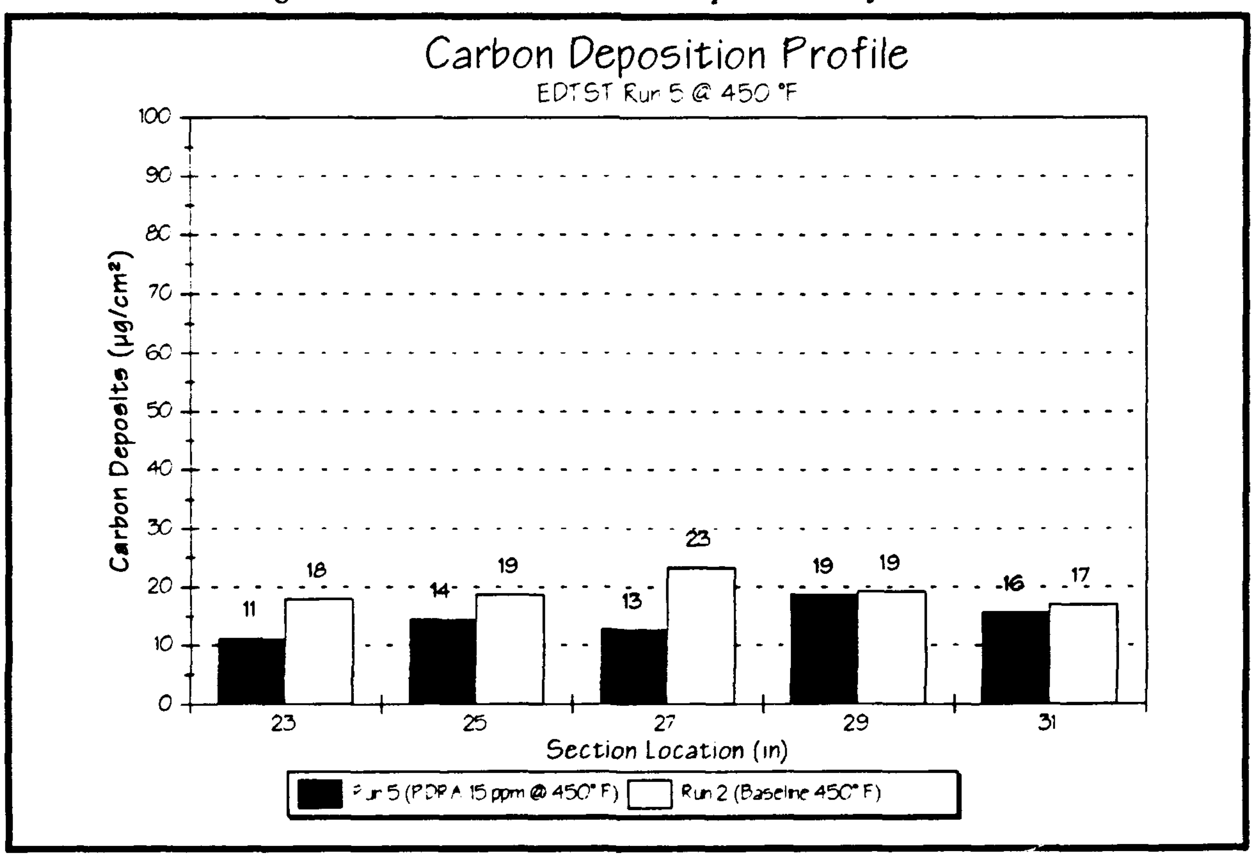

Figure 32 - EDTST Runs 2 and 5 Deposition Profile, 450°F

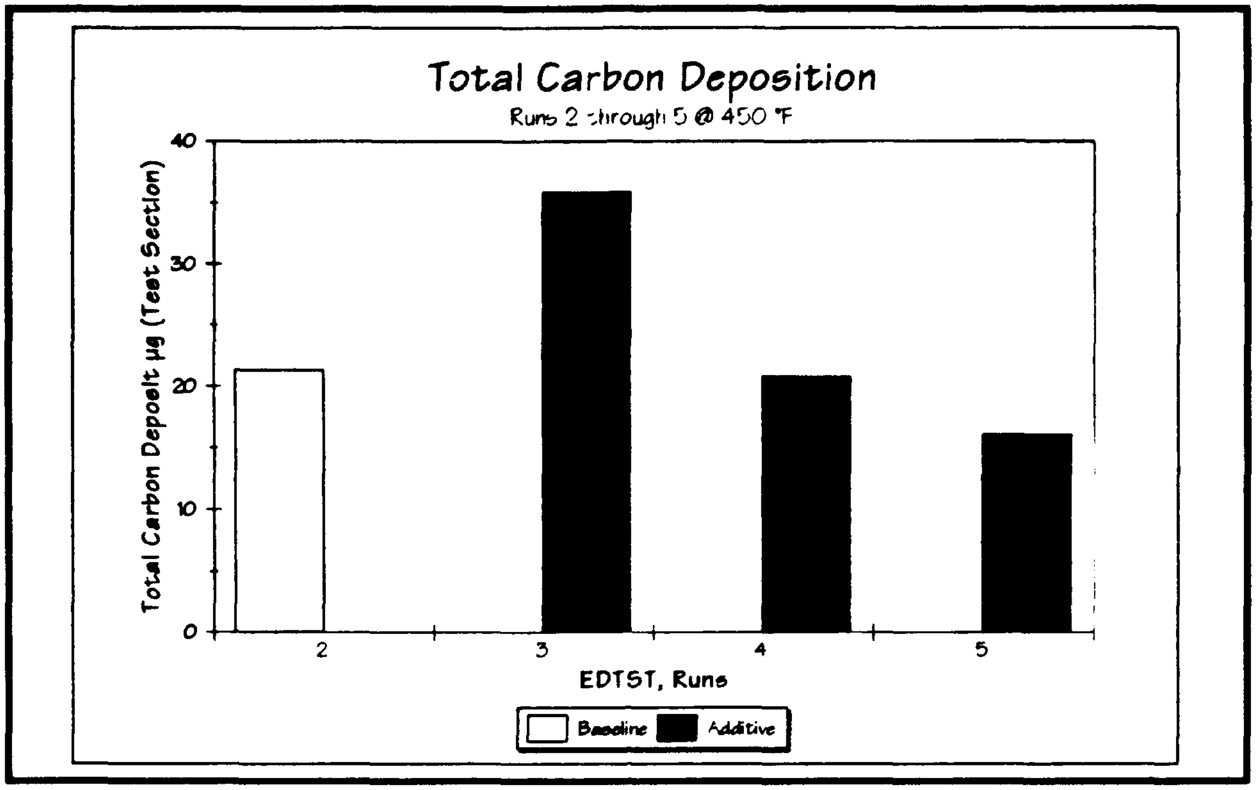

Figure 33 - EDTST Runs 2 through 5 Deposition Profile

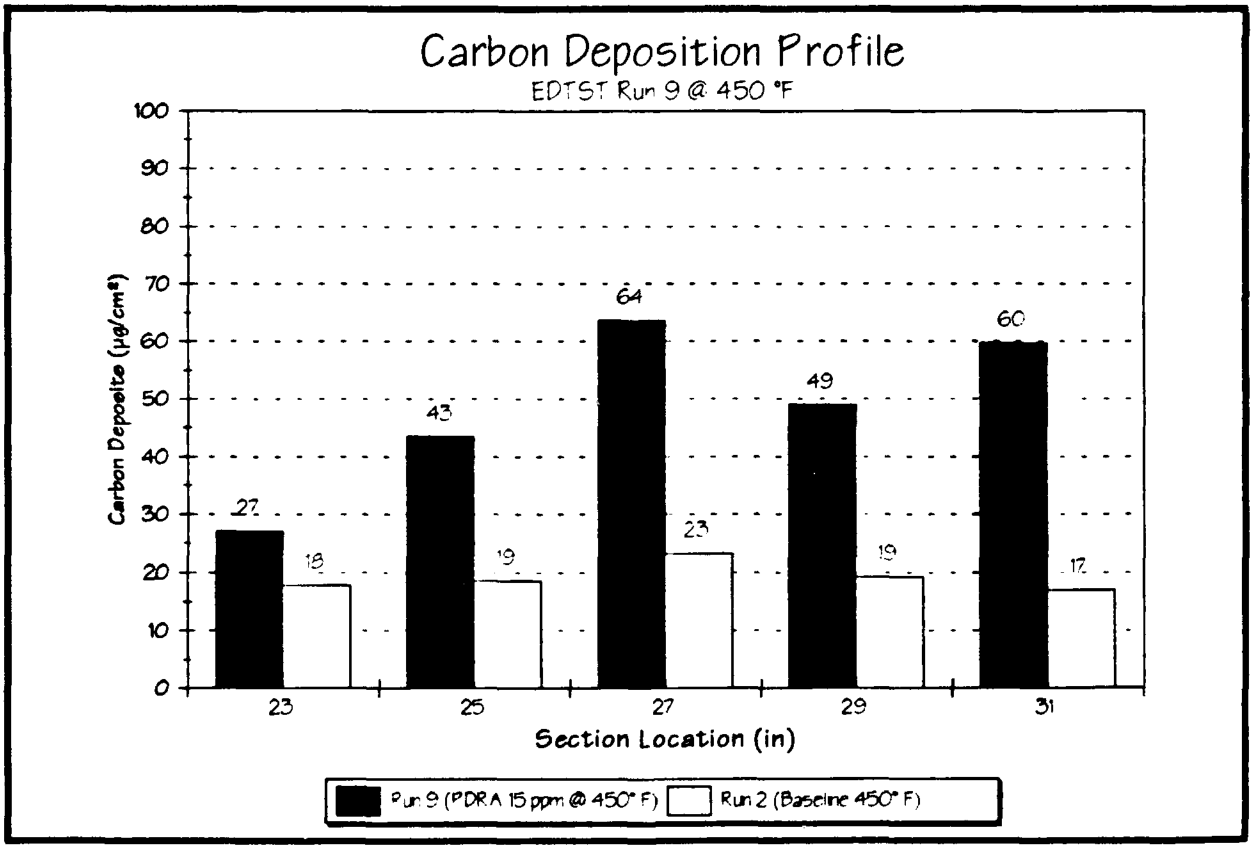

Figure 34 - EDTST Runs 2 and 9 Deposition Profile, 450°F

wetted-wall temperature of 450 °F. Leco carbon analysis results for these tests are shown in Figures 34 and 35.

The results of these tests indicated that the deposits were greater for fuel with PDRA at both 450 °F and 480 °F temperatures. These results correlated with the results of the FSS tests for the same fuel blends except that the overall magnitude of the carbon deposits is greater for the FSS because the increased total fuel flow (over 4 times higher for the FSS than for the EDTST) and the time/temperature history factor of the FSS.

Another test (EDTST Run 7) was also conducted with the baseline fuel. It was intended that the heater section tube maximum wetted wall temperature of 450 °F be the test point for Run 7 for correlation purposes. However, during the test it was discovered that the heater section test tube had become bent at the bottom, presumably during placement of sand into the heater test section furnace tube. This resulted in a higher temperature at the bottom thermocouple than at the middle thermocouple, where the highest temperature normally occurs. By the time this problem was

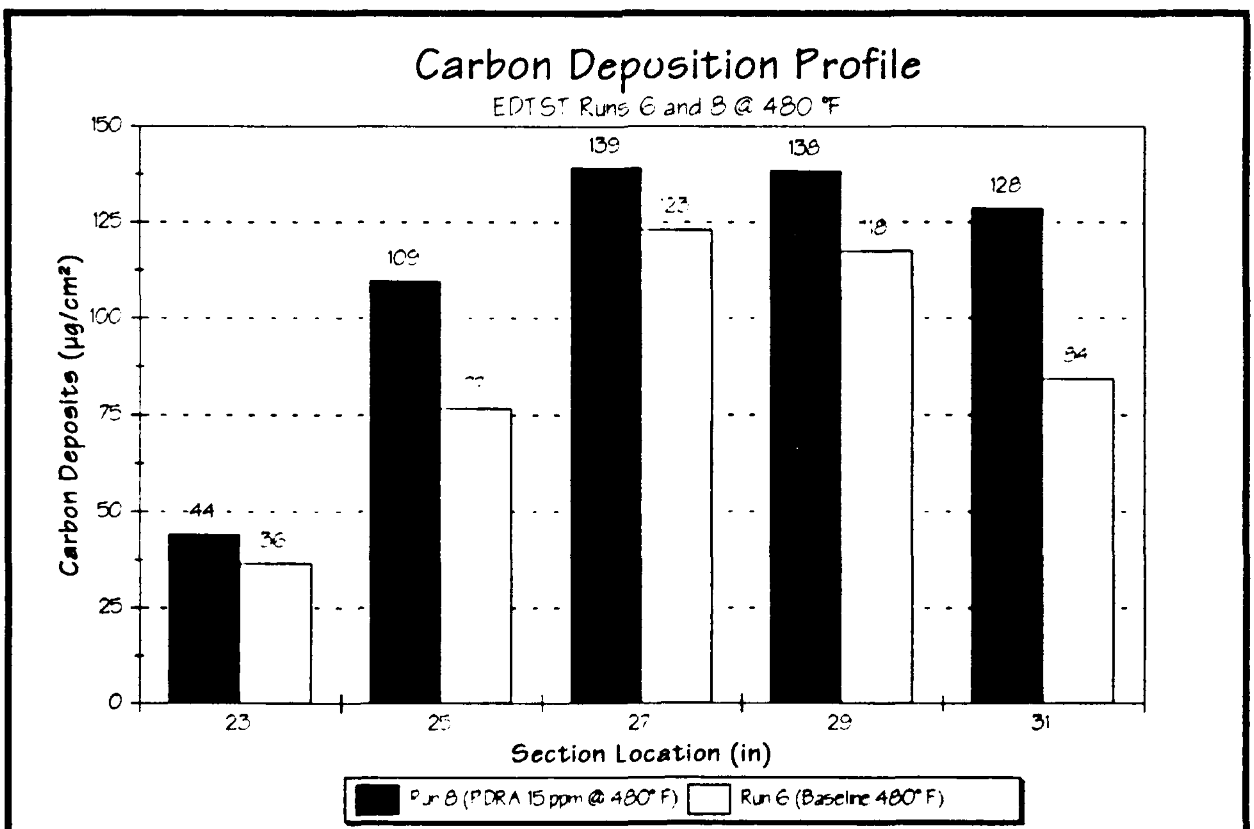

Figure 35 - EDTST Runs 6 and 8 Deposition Profile, 480°F

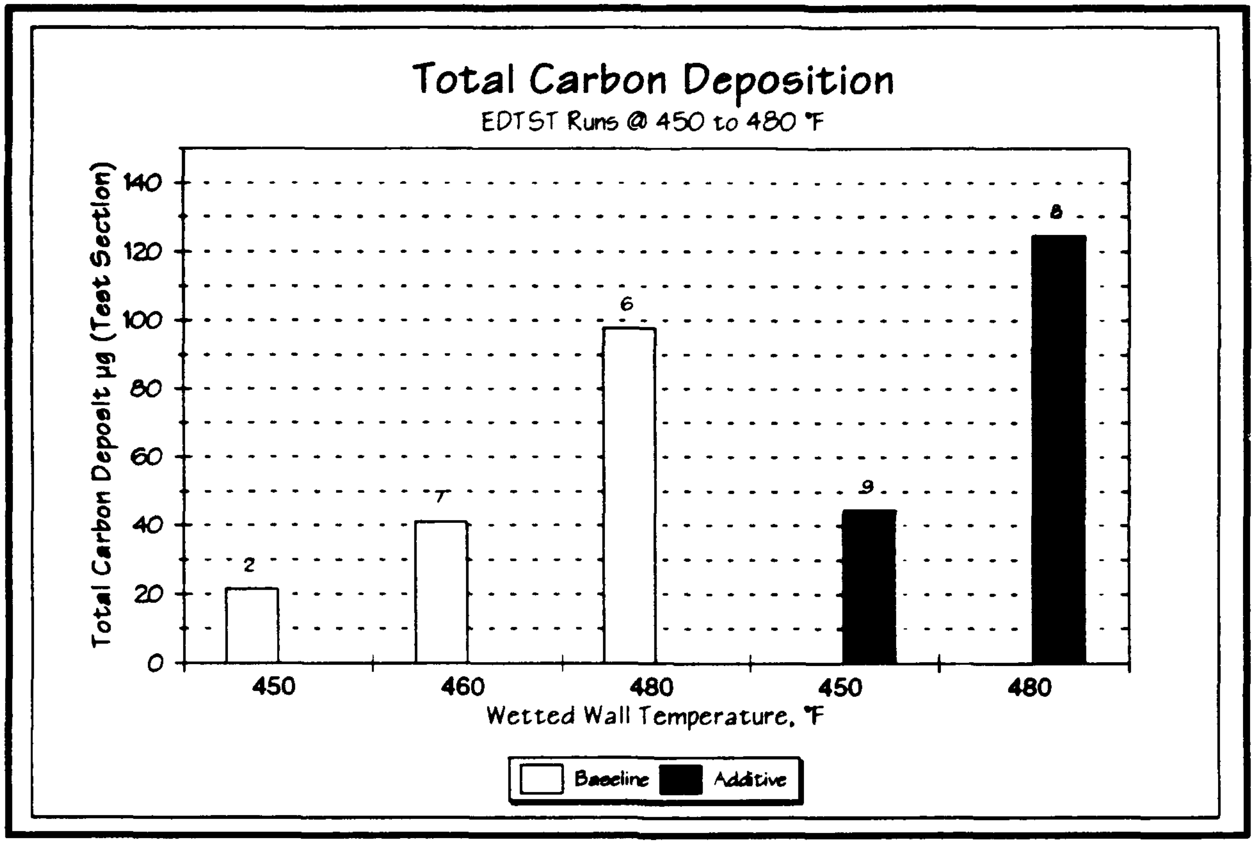

Figure 36 - EDTST Total Carbon Deposition vs Temperature

discovered, the test had progressed too long to be concerned about correcting the problem. Even though a direct correlation could not be achieved, the carbon burnoff results of this test did indicate good correlation when compared with the baseline tests at 450 °F and 480 °F as shown in Figure 36.

AUGMENTOR VAPORIZATION FOULING RIG (AVFR)

Early in this test program, several tests were conducted on fuels with and without PDR additive in the Augmentor Vaporization Fouling Rig. These tests were conducted with both of the initial baseline fuels (JP-8 and JP-5) which were used in Runs 0 through 8 in the FSS. Concentrations of 15 and 50 wppm were evaluated. Results of this testing is presented in Table 9. The JP-8 fuel with 50 wppm additive indicated a carbon deposition increase of approximately 50% when compared to the baseline itself. The JP-5 with 15 wppm additive indicated a carbon deposition increase of approximately 27% when compared to the baseline fuel itself.

TABLE 9 - Augmentor Rig Deposition Data

Fuel Used	PDRA Added (ppm by weight)	Deposition (Vaporization) (μg)
JP-8	0	2503, 3290
JP-8	50 wppm	4891
JP-5	0	3101
JP-5	15 wppm	3935

SECTION 9
CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS:

Based on the data presented in this report, the following conclusions can be drawn:

- Evaluations in the FSS, EDTST and AVFR resulted in more carbon deposition in fuels containing CDR®102M than in those same fuels without CDR®102M.
- The use of a pipeline drag reducing additive, in particular, CDR®102M, in aviation turbine fuels will result in increased carbon deposition in engine fuel injection nozzles and manifolds where fuel-wetted wall temperatures are 450 °F or greater. This includes engine augmentor spray bars and rings.
- The increased carbon deposition associated with the use of CDR®102M will result in increased maintenance requirements for some present production engines as well as some engines now in development.
- Future engine trends indicate that increased bulk fuel and engine nozzle wetted wall temperatures will make the use of CDR®102M even more unattractive from a thermal stability standpoint.

RECOMMENDATIONS:

It is recommended that CDR®102M and other similar drag reducing additives NOT BE APPROVED for general use in either military or commercial aviation turbine fuels.

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4. Edwards, Timothy J., WL/POSF, Wright-Patterson Air Force Base, Ohio, "Deposition During Vaporization of Jet Fuel in a Heated Tube," AIAA Paper 92-0687, January 9, 1992.

5 Hale,Gary C., Major, USAF, "Development of Mission Profiles for a Reduced Scale Aircraft Engine/Airframe Fuel System Simulator," Technical Report AFWAL-TR-88-2100, September 1988.

6. McDonnell Aircraft, "Flight Manual, USAF Series F-15 A/B/C/D Aircraft," Contract Numbers F33657-70-C-0300, F09603-83-D-0295 and F33657-79-C-0779, 15 January 1984.

7. Beal,George, Pratt & Whitney, Government Products Division, "Fuel-Engine-Airframe Optimization Study," Technical Report, pp. 54-60, AFWAL-TR-85-2050, September 1985.

8. Letter, Conoco Specialty Products, Mr. Timothy J. Mitchel, dated 30 March 1993.

APPENDIX A

PROCEDURE FOR PREPARATION AND ANALYSIS OF THE BURNER FEED ARM FOR THE REDUCED SCALE FUEL SYSTEM SIMULATOR (FSS)

PRE-TEST PREPARATION

The FSS BFA is constructed of two lengths of stainless steel tubing with one tube being drawn inside another to give it the desired wall thickness. This composite tube is machined to a total length of 12 inches, 10 inches of which are heated in the RF induction field. Figure A-1 is a detailed drawing of the construction of the current BFA. Figure A-2 is a diagram of thermocouple placement and thermocouple name assignments.

Preparation of the BFA for use is primarily a matter of installing the Swageloc nuts, thermocouple installation, and cleaning. Since the BFA is a machined tube, there may be cutting oils present after the machining process. There may also be oils on the thermocouples or the nichrome thermocouple straps. These oils must be removed prior to BFA use. The steps below give the procedure for attaching thermocouples and cleaning the BFA prior to use. These steps assume that the BFA has already been fabricated.

The first step is to clean the exterior and the interior of the BFA. First, thoroughly rinse the inside and outside of the BFA with acetone to remove any heavy machine oils that may be present. Follow the acetone rinse with a heptane or iso-octane rinse.

Next, attach the four thermocouples (TE58, TE59, TE60 and TE61) to the exterior of the BFA as indicated in Figure A-2. Use type K thermocouples with a nominal diameter of 0.020 inch. It is important that the thermocouples be securely attached. To attach the thermocouple, gently bend the last 3/8 inch of the thermocouple near the tip into a hook shape. Position the tip of the thermocouple on the BFA skin and hold in place. Cover the tip of the thermocouple with a small strip of nichrome ribbon wire and tack or spot weld the strap in place. Place additional tacks as

close as possible to the thermocouple tip being careful NOT to tack the thermocouple itself. The thermocouples must have good contact with the BFA surface in order to give consistent measurements. Once thermocouples have been attached, use a thermocouple calibration device or thermocouple reader to make sure that they are still functioning properly. Jiggle the thermocouples to make sure there are no wire breaks during installation.

Do a final cleaning of the BFA with the thermocouples attached to remove any residual oils from the thermocouples. To do this, submerge the entire BFA assembly in a cleaning solution of 50% distilled water and 50% "Beyond 2001" liquid cleaner (or "Blue Gold" cleaner) in an ultrasonic cleaner. These two cleaners are the only two proven acceptable for use on components where Leco Carbon Burn-off analyses will eventually be done because they do not leave a residue behind. Clean for about 30 minutes in the ultrasonic cleaner. After 30 minutes, replace the 50/50 cleaning solution with pure, clean distilled water and ultrasonically rinse the BFA assembly for another 30 minutes.

From this point forward, handle the BFA with nylon or cotton gloves to avoid contaminating the BFA with body oils. After the ultrasonic rinse, hand rinse the BFA with about 100 ml distilled water. Follow the water rinse with an acetone rinse. Follow the acetone rinse with a heptane rinse. Use about 100 ml for each rinse. Using tongs or gloves, place the BFA assembly in a vacuum oven and dry at 100 F for 1 hour.

After the BFA is dry, install the BFA in FSS. Use gloves and avoid getting oils and grease on the BFA. Do not use thread lubricants unless it is absolutely necessary. If you have to use thread lubricants, use the minimum amount necessary and make absolutely sure the lubricant does not get inside the BFA.

Install the interior thermocouples by inserting them into the drilled holes in the BFA after it has been installed into the system. You may need to use a silicone heat sink material to make sure the thermocouples are making good thermal contact inside the thermocouple holes. Use as little as possible. Make sure the thermocouples are installed all the way inside these holes. If they are not installed properly, they will not give the proper readings.

POST-TEST ANALYSIS

Once the test is completed, the BFA must be removed for sectioning and analysis. This removal may be difficult in that the metal fittings that hold the BFA in place may have become seated from the heat. Removal must be done with extreme care. There may be deposits inside the tube which will come out if the tube is mishandled.

Once removed from the FSS, carefully remove the thermocouples from the BFA. Wherever possible, remove as much of the nichrome ribbon wire as possible. Do not "chisel" these straps off. It is acceptable to leave a few of them on if necessary.

Having removed the thermocouples and as much of the nichrome strap as possible, gently rinse the BFA inside and out with about 100 ml of heptane. This will remove any residual fuel that may be on the surfaces. As much as is possible, handle the BFA using lint-free cotton or nylon gloves. Place the BFA in a vacuum oven at 100 F for 1 hour to remove residual fuel and heptane.

After 1 hour, remove the BFA and have it cut into 1-inch segments by EDM. Figure A-2 shows how the BFA is to be cut. Make sure that the EDM operator is aware of the delicate nature of the BFA and the deposits that it may contain. Also make sure they know not to use cutting oils. They should only use clean water in the EDM (as much as possible).

Once the BFA has been sectioned, gently rinse each segment in heptane. Use about 100 ml for all 12 sections of the BFA. Make sure all segments are marked so that you can easily tell which is which. Once rinsed, place all segments in a vacuum oven at 100 F for 3 or more hours. After 3 hours, remove the segments from the oven and store them either under a vacuum or in a desiccator until Leco Carbon Analyses can be done. Carbon analyses should be run within 8 hours of being removed from the vacuum oven. However, if the segments are stored under vacuum, then they can be stored for 24 or more hours. In any case, all carbon analyses should be completed within 48 hours of receipt of the BFA segments from the machine shop.

Wherever possible, run all segments on the same Leco analyzer to eliminate subtle differences between analyses which can contribute to data scatter.

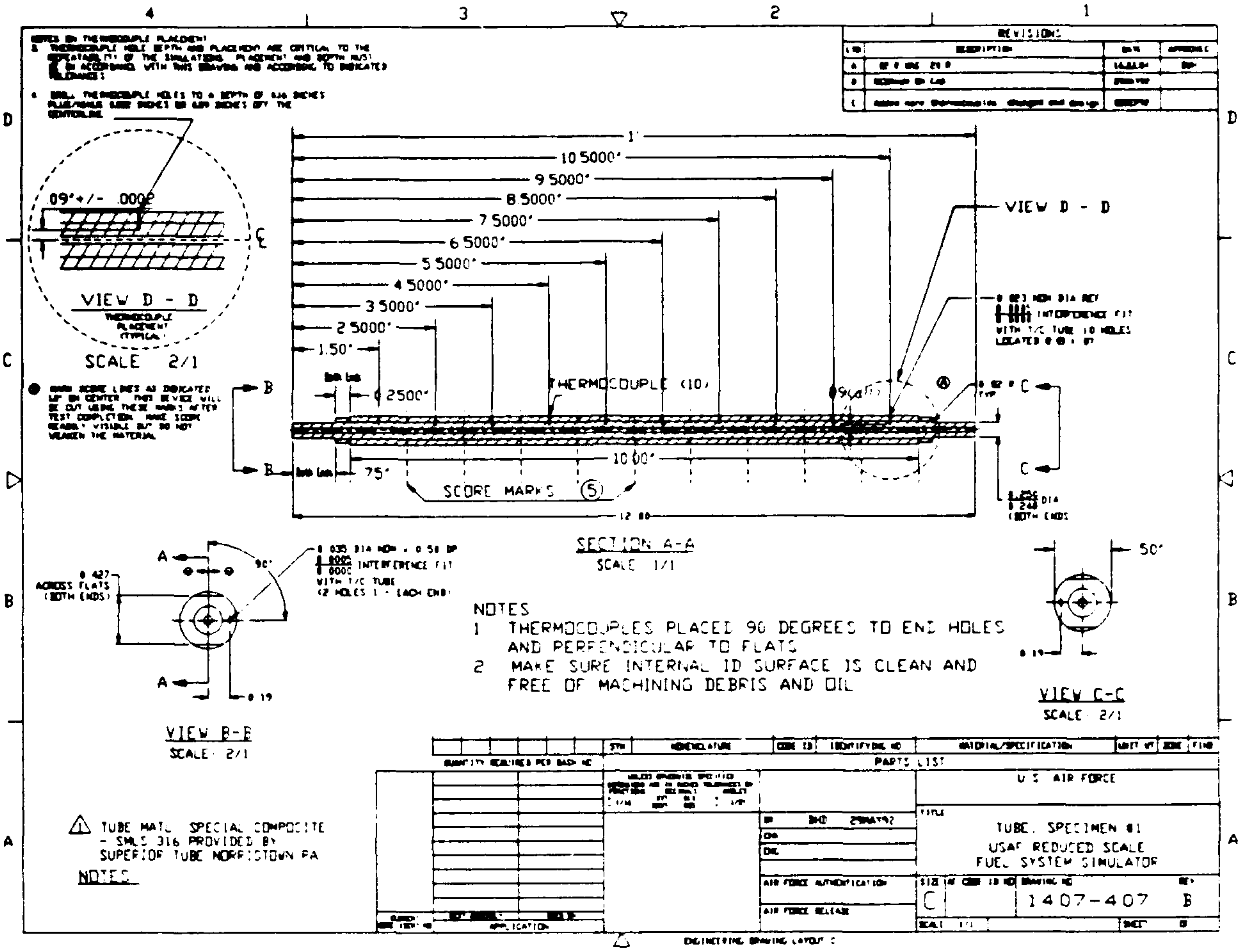

Figure A-1 Burner Feed Arm Assembly

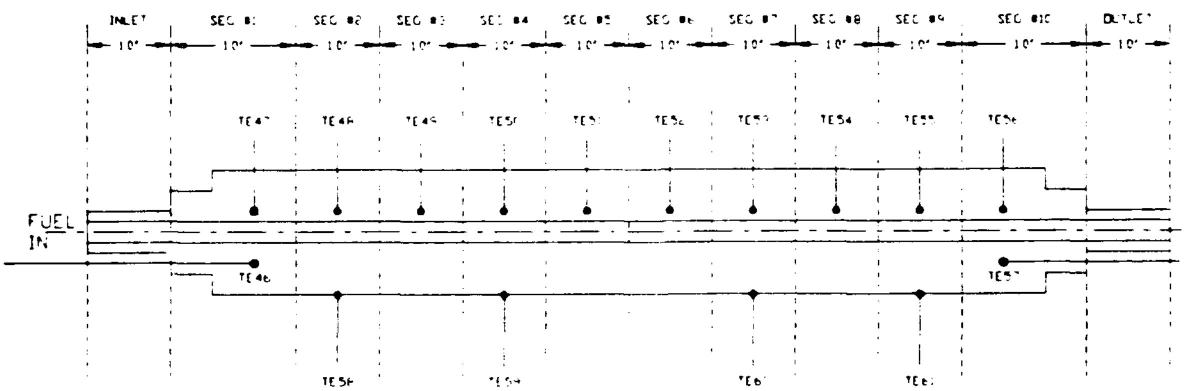

Figure A-2 BFA Thermocouple Placement and Cutting Guide

APPENDIX B

FUEL/ADDITIVE BLEND ANALYSIS
CONOCO, PONCA CITY

In order to verify the proper blending of the Conoco drag reducing additive into the Jet-A fuel stock used for testing during this program, a sample of blended fuel was taken from the main fuel farm tank used for the simulator runs. This sample was analyzed by Conoco to determine additive concentration in terms of parts per million polymer.

Multiple analyses were performed on fuel samples sent to Conoco. The results indicated actual additive concentrations of between 12.5 and 13.8 parts per million polymer. This is slightly less than the target value of 15 parts per million and was probably due either to the incomplete removal of additive material from blending stock drums or from incomplete blending. The nature of the additive makes complete and total dissolution of the additive in the fuel very difficult. Even though the measured concentrations were between 1.2 and 2.5 parts per million lower than the target value, it is unlikely that this negligible difference would affect the overall results of this program.

In addition to performing analyses to determine additive concentration, Conoco also performed analyses directed at determining whether the additive blend was fully sheared. Again, samples were removed from the main fuel farm tank used for this program and the average molecular weight was determined. Results that the average molecular weight of all samples were approximately 1.2 million (Mw). In a summary report from Conoco, it was reported that "this is well below the 3 million (Mw) generally accepted as being fully sheared."[8] It is important to note that this degree of shearing was accomplished only by recirculating the fuel within the fuel farm facility. The fuel was, therefore, fully sheared before entering the FSS test rig.

APPENDIX C

TEST PARAMETER SUMMARY

RUNS 0 THROUGH 18

Fuel System Simulator Run Summary

Run No.: 0	Fuel ID Number: 183	
Run Hrs: 130	Fuel Name: JP-8	
Configuration: F-15/F10C	Control Mode: MISSIONS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	480		
BFA Bulk Fuel Out, °F	350	375	

TEST RESULTS

Start Date: 17 Oct 1990	End Date: 7 Dec 1990	Actual Run Hours: 127
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 480	Seg #9 End Temp: 480	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Total BFA Carbon, μg:
Carbon, $\mu g/cm^2$:
Carbon, $\mu g/cm^2 hr$:

NOTES:

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Fuel System Simulator Run Summary

Run No.: 1	Fuel ID Number: 2990	
Run Hrs: 130	Fuel Name: JP-8 + 50 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: MISSIONS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350	375	

TEST RESULTS

Start Date: 3 Aug 1990	End Date: 22 Aug 1990	Actual Run Hours: 127
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	µgrams Carbon	Delta-Temp
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Total BFA Carbon, µg:
Carbon, µg/cm²:
Carbon, µg/cm²hr:

NOTES:

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Fuel System Simulator Run Summary

Run No.: 2	Fuel ID Number: 2990	
Run Hrs: 130	Fuel Name: JP-8 + 50 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: MISSIONS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350	375	

TEST RESULTS

Start Date: 21 Jan 1991	End Date: 20 Feb 1991	Actual Run Hours: 127
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Total BFA Carbon, μg:
Carbon, $\mu g/cm^2$:
Carbon, $\mu g/cm^2 hr$:

NOTES:

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Fuel System Simulator Run Summary

Run No.: 3	Fuel ID Number: 2991	
Run Hrs: 130	Fuel Name: JP-5 + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: MISSIONS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350	375	

TEST RESULTS

Start Date: 15 Mar 1991	End Date: 3 Apr 1991	Actual Run Hours: 127
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Total BFA Carbon, μg:
Carbon, $\mu g/cm^2$:
Carbon, $\mu g/cm^2 hr$:

NOTES:

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Fuel System Simulator Run Summary

Run No.: 4	Fuel ID Number: 2817	
Run Hrs: 130	Fuel Name: JP-5	
Configuration: F-15/F100	Control Mode: MISSIONS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350	375	

TEST RESULTS

Start Date: 14 May 1991	End Date: 10 Jul 1991	Actual Run Hours: 127
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		

Total BFA Carbon, μg:	
Carbon, μg/cm²:	
Carbon, μg/cm²hr:	

NOTES:

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Fuel System Simulator Run Summary

Run No.: 5	Fuel ID Number: 2817	
Run Hrs: 130	Fuel Name: JP-5	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 15 Jan 1992	End Date: 24 Jan 1992	Actual Run Hours: 130
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	600.0000	
2	4,410.0000	
3	5,017.0000	
4	5,590.0000	
5	7,770.0000	
6	11,600.0000	
7	13,300.0000	
8	13,700.0000	
9	13,500.0000	
10	6,770.0000	

Total BFA Carbon, μg:	82,257.0000
Carbon, μg/cm²:	62,438.8900
Carbon, μg/cm²hr:	480.2992

NOTES:

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Fuel System Simulator Run Summary

Run No.: 6	Fuel ID Number: 2817	
Run Hrs: 130	Fuel Name: JP-5	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 29 Jan 1992	End Date: 5 Feb 1992	Actual Run Hours: 122
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	327.0000	
2	721.0000	
3	1,320.0000	
4	1,500.0000	
5	2,010.0000	
6	3,090.0000	
7	5,060.0000	
8	6,660.0000	
9	5,200.0000	
10	1,240.0000	

Total BFA Carbon, μg:	27,128.0000
Carbon, μg/cm²:	20,592.0800
Carbon, μg/cm²hr:	168.7875

NOTES:

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Fuel System Simulator Run Summary

Run No.: 7	Fuel ID Number: 2992	
Run Hrs: 132	Fuel Name: JP-5 + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 11 Feb 1992	End Date: 19 Feb 1992	Actual Run Hours: 132
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	311.0000	
2	400.0000	
3	742.0000	
4	1,010.0000	
5	1,550.0000	
6	2,140.0000	
7	3,000.0000	
8	3,630.0000	
9	3,430.0000	
10	675.0000	

Total BFA Carbon, μg:	16,668.0000
Carbon, μg/cm²:	12,819.1900
Carbon, μg/cm²hr:	97.1151

NOTES:

Perform Pro Plus, 15 Mar 93 -

Fuel System Simulator Run Summary

Run No.: 8	Fuel ID Number: 2992	
Run Hrs: 130	Fuel Name: JP-5 + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	3000	
Seg#9 Wetted Wall, °F	475		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 20 Feb 1992	End Date: 27 Feb 1992	Actual Run Hours: 130
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 475	Seg #9 End Temp: 475	Seg #9 Delta-T: 0
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	246.0000	
2	270.0000	
3	673.0000	
4	1,180.0000	
5	1,920.0000	
6	3,160.0000	
7	4,890.0000	
8	6,850.0000	
9	6,790.0000	
10	1,560.0000	

Total BFA Carbon, μg:	27,539.0000
Carbon, μg/cm²:	20,904.0500
Carbon, μg/cm²hr:	160.8004

NOTES:

Perform Pro Plus, 15 Mar 93 -

Fuel System Simulator Run Summary

Run No.: 9	Fuel ID Number: 2926	
Run Hrs: 100	Fuel Name: Jet-A	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	480		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 5 Aug 1992	End Date: 10 Aug 1992	Actual Run Hours: 78
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 480	Seg #9 End Temp: 558	Seg #9 Delta-T: 78
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	299.0000	10
2	288.0000	30
3	341.0000	32
4	495.0000	41
5	745.0000	52
6	882.0000	59
7	1,240.0000	72
8	1,820.0000	82
9	2,350.0000	78
10	1,460.0000	48

Total BFA Carbon, μg:	9,920.0000
Carbon, μg/cm²:	752.9800
Carbon, μg/cm²hr:	9.5920

NOTES:

Fuel System Simulator Run Summary

Run No.: 10	Fuel ID Number: 2926	
Run Hrs: 100	Fuel Name: Jet-A	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	450		
BFA Bulk Fuel Out, °F	340		

TEST RESULTS

Start Date: 10 Aug 1992	End Date: 16 Aug 1992	Actual Run Hours: 94
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 453	Seg #9 End Temp: 520	Seg #9 Delta-T: 67
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	250.0000	12
2	187.0000	39
3	284.0000	41
4	332.0000	53
5	384.0000	61
6	397.0000	60
7	450.0000	64
8	554.0000	68
9	524.0000	67
10	281.0000	21

Total BFA Carbon, μg:	3,643.0000
Carbon, μg/cm²:	276.5200
Carbon, μg/cm²hr:	2.9293

NOTES:

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Fuel System Simulator Run Summary

Run No.: 11	Fuel ID Number: 2993	
Run Hrs: 100	Fuel Name: Jet-A + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	450		
BFA Bulk Fuel Out, °F	340		

TEST RESULTS

Start Date: 21 Aug 1992	End Date: 28 Aug 1992	Actual Run Hours: 96
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 454	Seg #9 End Temp: 522	Seg #9 Delta-T: 68
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	329.0000	8
2	260.0000	24
3	216.0000	38
4	222.0000	43
5	273.0000	50
6	457.0000	61
7	540.0000	71
8	718.0000	75
9	744.0000	68
10	417.0000	33

Total BFA Carbon, μg:	4,176.0000
Carbon, μg/cm^2:	316.9800
Carbon, μg/cm^{2}hr:	3.3019

NOTES:

Fuel System Simulator Run Summary

Run No.: 12	Fuel ID Number: 2993	
Run Hrs: 100	Fuel Name: Jet-A + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	480		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 1 Sep 1992	End Date: 4 Sep 1992	Actual Run Hours: 65
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 483	Seg #9 End Temp: 567	Seg #9 Delta-T: 84
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	178.0000	6
2	154.0000	22
3	219.0000	39
4	98.0000	52
5	306.0000	67
6	337.0000	81
7	422.0000	89
8	490.0000	92
9	517.0000	84
10	316.0000	52

Total BFA Carbon, μg:	3,037.4000
Carbon, μg/cm²:	230.5500
Carbon, μg/cm²hr:	3.5092

NOTES:

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Fuel System Simulator Run Summary

Run No.: 13	Fuel ID Number: 2926	
Run Hrs: 100	Fuel Name: Jet-A	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	480		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 15 Oct 1992	End Date: 19 Oct 1992	Actual Run Hours: 69
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 482	Seg #9 End Temp: 610	Seg #9 Delta-T: 128
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	216.0000	11
2	232.0000	46
3	309.0000	64
4	375.0000	75
5	495.0000	91
6	597.0000	106
7	736.0000	119
8	765.0000	128
9	1,230.0000	128
10	797.0000	79

Total BFA Carbon, μg:	5,752.0000
Carbon, μg/cm²:	436.6000
Carbon, μg/cm²hr:	6.2731

NOTES:

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Fuel System Simulator Run Summary

Run No.: 14	Fuel ID Number: 2994	
Run Hrs: 100	Fuel Name: Jet-A + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	480		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 23 Oct 1992	End Date: 27 Oct 1993	Actual Run Hours: 76
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 480	Seg #9 End Temp: 614	Seg #9 Delta-T: 134
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	226.0000	8
2	260.0000	44
3	470.0000	77
4	665.0000	97
5	883.0000	114
6	1,150.0000	128
7	1,740.0000	141
8	2,760.0000	152
9	2,280.0000	134
10	582.0000	58

Total BFA Carbon, μg:	11,016.0000
Carbon, $\mu g/cm^2$:	836.1700
Carbon, $\mu g/cm^2 hr$:	11.0020

NOTES:

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Fuel System Simulator Run Summary

Run No.: 15	Fuel ID Number: 2994	
Run Hrs: 100	Fuel Name: Jet-A + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	460		
BFA Bulk Fuel Out, °F	350		

TEST RESULTS

Start Date: 3 Nov 1992	End Date: 8 Nov 1992	Actual Run Hours: 100
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 461	Seg #9 End Temp: 581	Seg #9 Delta-T: 120
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	µgrams Carbon	Delta-Temp
1	207.0000	16
2	405.0000	61
3	606.0000	85
4	746.0000	98
5	878.0000	112
6	1,170.0000	126
7	1,490.0000	135
8	1,970.0000	140
9	1,840.0000	120
10	779.0000	67

Total BFA Carbon, µg:	10,091.0000
Carbon, $\mu g/cm^2$:	765.9600
Carbon, $\mu g/cm^2 hr$:	7.6596

NOTES:

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Fuel System Simulator Run Summary

Run No.: 16	Fuel ID Number: 2926	
Run Hrs: 100	Fuel Name: Jet-A	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	420		
BFA Bulk Fuel Out, °F	330		

TEST RESULTS

Start Date: 13 Nov 1992	End Date: 18 Nov 1992	Actual Run Hours: 98
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 423	Seg #9 End Temp: 486	Seg #9 Delta-T: 63
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	160.0000	
2	248.0000	
3	304.0000	
4	392.0000	
5	424.0000	
6	486.0000	
7	552.0000	71
8	635.0000	
9	573.0000	63
10	252.0000	

Total BFA Carbon, μg:	4,026.0000
Carbon, μg/cm²:	305.5900
Carbon, μg/cm²hr:	3.1119

NOTES:

Fuel System Simulator Run Summary

Run No.: 17	Fuel ID Number: 2994	
Run Hrs: 100	Fuel Name: Jet-A + 15 wppm CDR-102M	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.06	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	420		
BFA Bulk Fuel Out, °F	330		

TEST RESULTS

Start Date: 19 Nov 1992	End Date: 23 Nov 1992	Actual Run Hours: 72
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 424	Seg #9 End Temp: 449	Seg #9 Delta-T: 25
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	µgrams Carbon	Delta-Temp
1	302.0000	2
2	334.0000	9
3	306.0000	13
4	293.0000	15
5	304.0000	21
6	336.0000	26
7	327.0000	25
8	305.0000	29
9	339.0000	25
10	281.0000	10

Total BFA Carbon, µg:	3,127.0000
Carbon, µg/cm²:	237.3500
Carbon, µg/cm²hr:	3.2966

NOTES:

Perform Pro Plus, 15 Mar 93 -

Fuel System Simulator Run Summary

Run No.: 18	Fuel ID Number: 2926	
Run Hrs: 100	Fuel Name: Jet-A	
Configuration: F-15/F100	Control Mode: SETS	Farm Tank: S-15

TARGET CONDITIONS

COMPONENT	CRUISE	IDLE DESCENT	
Core Fuel Flow, gph	4.09	2.55	
AFHX Bulk Fuel Out, °F	225	225	
FCOC Bulk Fuel Out, °F	300	300	
Seg#9 Wetted Wall, °F	420		
BFA Bulk Fuel Out, °F	330		

TEST RESULTS

Start Date: 30 Nov 1992	End Date: 4 Dec 1992	Actual Run Hours: 72
Sets Started:	Sets Finished:	Cycles, Total:
Seg #9 Start Temp: 424	Seg #9 End Temp: 441	Seg #9 Delta-T: 17
Fuel Used (gal):		

CARBON ANALYSIS

Segm't	μgrams Carbon	Delta-Temp
1	291.0000	5
2	324.0000	17
3	288.0000	23
4	344.0000	19
5	325.0000	18
6	342.0000	16
7	363.0000	17
8	373.0000	18
9	469.0000	17
10	349.0000	7

Total BFA Carbon, μg:	3,468.0000
Carbon, μg/cm²:	263.2400
Carbon, μg/cm²hr:	3.6409

NOTES: